EXHIBIT DX25

TO DECLARATION OF COREY L. GORDON IN SUPPORT OF DEFENDANTS' OPPOSITION TO PLAINTIFFS' MOTIONS TO EXCLUDE TESTIMONY OF THEODORE HOLFORD AND JONATHAN BORAK

FAEGRE BAKER DANIELS

IN THE HIGH COURT OF JUSTICE

CLAIM NO: CR 2016-520

QUEENS BENCH DIVISION

IN THE MATTER OF THE EVIDENCE (PROCEEDINGS IN OTHER JURISDICTIONS) ACT 1975

AND

IN THE MATTER OF CPR PART 34

AND

IN THE MATTER OF A CIVIL MATTER NOW PROCEEDINGS BEFORE THE UNITED STATES DISTRICT COURT FOR THE DISTRICT OF MINNESOTA ENTITLED AS FOLLOWS:

IN RE: BAIR HUGGER FORCED AIR WARMING PRODUCTS LIABILITY LITIGATION

MDL NO. 15-2666(JNE/FLN)

Plaintiffs

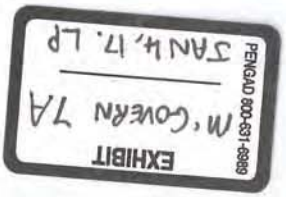
-v-

3M COMPANY AND ARIZANT HEALTHCARE INC.

Defendants

DOCUMENTS PROVIDED BY DR PAUL MCGOVERN VOLUME 5

PAGES 1987 - 2528



Document Name: Manuscript_Reed_1.pdf

Forced Air Warming and Ultra-Clean Ventilation Do Not Mix: The effect of excess vented heat on clean-airflow patterns.

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Key words: surgical site infection, forced air warming, laminar air flow, operating room environmental contamination, operating room ventilation

Abstract

Introduction: Ultra-clean ventilation is designed to protect the surgical site from airborne pathogens. However, ventilation performance is fragile and depends critically on airflow volumes and temperature gradients. Patient warming systems represent a disruption risk via the excess heat they release. Therefore, we compared the effects of two patient warming systems – (1) conductive fabric and (2) forced air – on clean-airflow patterns over the surgical site during orthopedic and spinal implant procedures.

Methods: A mannequin was draped for (1) a hip prosthesis and (2) a lower lumbar spinal implant in a partial-walled ultra-clean theater. Neutral buoyancy detergent bubbles were released under the anaesthesia drape and at floor level to visualize air-currents and assess the mobilization of resident air into the clean-airflow over the surgical site. For the hip prosthesis, a randomized design assessed the effects upperbody warming system and anesthesia drape height on bubbles reaching the surgical site. For the spinal, the effect of lowerbody warming system was assessed with time-lapsed-photography of bubbles. Lastly, joint sepsis rates were tracked for a 2 year period over which a change from forced air to conductive fabric was implemented.

Results: For the hip prosthesis, bubble counts were significantly higher for forced air than conductive fabric for laid-down (3 versus 0; $p=0.010$) and half-height (68 versus 0; $p<0.001$) anesthesia draping; differences for full-height draping were insignificant (1 versus 0; $p=0.283$). For the spinal, time-lapsed-photography showed forced air to establish upwards convection currents that transported floor air into the surgical site; this convection current was not present with conductive fabric. Joint sepsis infection rates were reduced after the implementation of conductive fabric warming (0% for n=161) versus prior rates with forced air (3.0% for n=936).

Conclusion: Excess heat from forced air warming disrupted clean-airflow patterns over the surgical site and generated upward convection currents, which transported non-sterile air from the floor and the anaesthesia side of the drape into the surgical site; conductive fabric warming had no such effects. Observation of joint sepsis rates suggests an empirical reduction in infection with conductive fabric warming in orthopedics.

Number of words: 339

Introduction

Although most famously remembered for pioneering the hip arthroplasty, Sir John Charnley was among the first to recognize the critical role of operating theater (OT) ventilation in preventing joint sepsis. Charnley postulated that the "surgical implant might provide a nidus for the growth of airborne bacteria which ordinarily are accepted as non-pathogenic.[1]" Research efforts confirmed Charnley's insights through animal studies and a national clinical trial involving over 8000 operations that demonstrated the efficacy of clean air for the reduction of arthroplasty infection rates.[3] As such, ultra-clean ventilation became the standard for orthopedic procedures. Ultra-clean ventilation protects the surgical site from airborne contamination through the constant delivery of a downward uniform velocity (0.3 to 0.5 m/s) highly filtered (>99.997%) airflow.[4] However, the performance of ultra-clean ventilation depends critically on air-flow volumes and proper temperature gradients,[6] the latter of which may be disrupted by excess heat released from patient warming devices.

The vented airflow from forced air warming is released at 43°C, which is often 20°C above ambient OT conditions. The release of such thermal energy has the potential to establish temperature gradients that impede the downward velocity of the OT ventilation airflows. Further, reductions in downward flow velocity have been shown to increase contaminant entrainment into the surgical site. Moreover, the release of excess heat may generate convection currents that rise against the downward airflows and mobilize non-sterile floor-level air into the surgical site.

Air-free alternatives, such as conductive fabric warming, have been developed that are comparably effective to forced air for the prevention of surgical hypothermia. These alternatives have much higher thermal efficiencies than forced air warming and, therefore, release only a fraction of the excess heat. As such, there is a need to critically assess the impact of forced air warming versus air-free alternatives on ultra-clean ventilation performance. Specifically, we compared the effects of (1) conductive fabric and (2) forced air warming on clean-airflow patterns over the surgical site in a partial-walled ultra-clean OT during two procedures representing the variety of implantable

operations typically encountered: 1) a hip arthroplasty with upper-body warming, and 2) a lower lumbar spinal with lower-body warming. Ventilation airflow patterns were visualized using neutrally bouyant detergent bubbles and observational data on joint sepsis rates were compared for the period each warming device was in clinical use.

Methods

Ultra-Clean Operating Theater Characteristics:

Experiments were carried out in a partial-walled ultra-clean OT (ExFlow 90, Howorth, United Kingdom) used for orthopedic and spinal surgery at Wansbeck Hospital (Ashington, United Kingdom). Validation and verification checks per HTM 2025 showed the OT airflows to be within specification and having a mean velocity of 0.44 m/s two-meters off the floor, which is above the threshold required by the standards (0.38 m/s). However, a slight airflow imbalance was detected during validation testing due to the location of the theater prep room that affected the results of a single particle entrainment test; entrainment values were 12% at that location, which margninally exceeded the recommended threshold of 10%. This slight descrepency was unlikely to have any effect on the results of the study. Further, smoke testing detected normal airflow patterns under the canopy and the OT passed microbial contamination testing.

Airflow Visualization Procedures:

High intensity lighting was used to illuminate neutrally buoyant detergend bubbles having a 4 mm average diameter (referred to herein as "bubbles"). "Bubbles" were produced by a bubble generator (Sage Action, Ithaca, NY), which utilized a helium-mixed air supply, detergent, and centripetal bubble size classification filter. The bubble generator is specifically designed and validated for the visualization of air currents.[10] For photography, a digital camera (D300, Nikon, Melville, NY) was employed and shutter exposure time was set to ¼ of a second for time-lapsed-photography.

Experimental Setup: Hip Arthoplasty

A mannequin was laid in the supine position on an operating table (Table Mfgr ???) and draped with a 3-piece orthopedic kit (Molnlycke Health Care) in accordance with standard protocols (**Fig 1**). A surgeon, dressed in occlusive clothing with head gear (MFGR xxx), and an anaesthesiologist stood motionless in front of the surgical site and behind the anaesthesia screen. At the head of the operating table, the surgical drape was either: 1) clipped to the ceiling to create a barrier between the surgical site and anesthesia area (full-drape); 2) clipped to IV poles and raised 0.75 meters above the operating table

(half-drape); or 3) laid-down over the mannequin's head (laid-down). The experimental upper-body warming treatment was introduced under the drape and was either: 1) a torso forced air blanket (Bair Hugger Model 540, Arizant Healthcare, Eden Prairie, MN); or 2) a torso conductive fabric blanket (Hot Dog Model B110, Augustine Biomedical + Design, Eden Prairie, MN). The blankets were powered by standard controllers (conductive fabric - Model WC02, Augustine Biomedical + Design; forced air - Model 750, Arizant Healthcare). "Bubbles" were introduced at the neck of the mannequin to track under-drape resident air movements in the region where the excess patient warming heat was being released.

Experimental Setup: Lower lumbar spinal

The same mannequin was laid in the prone position on the operating table and four drapes were arranged in a "square" configuration (MFGR???) with the anaesthesia screen at full-height in accordance with standard protocols (**Fig 2**). A single surgeon stood motionless next to the surgical site for all experiments. The experimental lower-body warming treatment was introduced under the drape and was either: 1) a lower-body forced air blanket (Bair Hugger Model 525, Arizant Healthcare); or 2) a lower-body conductive fabric blanket (Hot Dog Model B103, Augustine Biomedical + Design). The blankets were powered by the same controllers as listed above. "Bubbles" were introduced at floor level between the surgeon's body and the operating room table in the region where the patient warming excess heat was being released.

Sampling Procedures

Hip Arthroplasty: Bubble counts over the surgical site were measured for each experimental treatment using a sequence of 5 photographs taken at 10 second intervals. The number of bubbles reaching the surgical site was determined by counting the number of bubbles in a 0.5 by 0.5 meter region over the surgical site in each photograph (**Fig 3**).
Lower Lumbar Spinal: Time-lapsed-photography was chosen over the use of bubble counts to show differences in ventilation performance between patient warming systems given the significant change in observed surgical site airflow patterns (see **Results**).

Experimental Design

Hip Arthroplasty: A replicated (n=2) $3^1 2^1$ full factorial design was employed to assess changes in bubble counts over the surgical site. The experimental factors considered were: 1) anaesthesia screen: laid-down, half-screen, or full-screen; and 2) patient warming device: conductive fabric or forced air.

Lower Lumbar Spinal: No design was employed or necessary to demonstrate the difference in ventilation performance between forced air and conductive fabric patient warming systems (see **Results**).

Statistical Analysis

A poisson regression model was fitted to the hip arthroplasty data having the sum of bubble counts for each experimental run (5 pictures) as the response and the two factors identified in the experimental design as predictors (including interaction). Reported values are predicted means (± standard error of the mean) for experimental factor combinations based upon maximum likelihood estimates. Wald tests were used for significance.

Joint Sepsis Data

Joint sepsis data was collected for all orthopedic operations performed at the hospital during the 2-year period prior to the study, with dates comprising 9/1/2008 to 9/1/2010. A trasition in patient warming systems from forced air to conductive fabric was made in all four orthopedic theaters starting 3/1/2010 and ending 6/1/2010.

Results

Hip Arthoplasty:

The number of bubbles reaching the surgical site measured the degree to which patient warming excess heat mobilized resident under-drape air over the anaesthesia screen and into the surgical site. Bubble counts per photograph (**Fig 4**) suggest that forced air warming generated sufficient excess heat to mobilize resident under-drape air over the anaesthesia screen. In contrast, conductive fabric warming did not generate sufficient excess heat to have the same mobilizing effect. Further, surgical drape position appeared to have a large effect on resident under-drape air mobilization into the surgical site for forced air warming, with the half-drape configuration resulting in the largest degree of resident-air mobilization.

Differences in the sum of bubble counts for each experimental run (**Fig 5**) were significant between conductive fabric and forced air warming for the drape configurations of half-drape (0 versus 68, $p<0.001$) and laid-down (0 versus 3, $p=0.010$); differences for full-drape (0 versus 1, $p=0.283$) were insignificant. It was necessary to model the sum of bubble counts for statistical inference, otherwise observations would not be independent.

Lower Lumbar Spinal:

Time-lapsed-photography showed forced air warming excess heat to generate hot-air convection currents that transported large quanties of floor-level resident air upwards and into the surgical site (**Fig 6**). These convection currents appeared to form in the space between the surgeon's body and the operating room table. In contrast, conductive fabric warming did not generate sufficient excess heat to establish such convection currents. Instead, with conductive fabric warming ventilation airflow patterns followed the intended path - downwards and away form the surgical site.

Joint Sepsis Rates:

A 2-year observation of orthopedic infections revealed a reduction in joint sepsis rates for the period conductive fabric warming was in clinical use versus forced air warming, with

average infection rates of 0.0% (n=161) versus 3.0% (n=936), respectively (**Fig 7**). There was a 3 month transition period where both patient warming devices were used in the orthopedic theaters.

Discussion

This study compared the effects of two patient warming systems, forced air and conductive fabric, on ventilation performance in an ultra-clean operating theater during spinal and orthopedic procedures. Forced air warming excess heat was found to generate convection currents that disrupted clean-airflow patterns over the surgical site during both procedures. In contrast, conductive fabric warming released minimal excess heat and was shown to have no effect on ventilation performance in either procedure. The results also showed forced air warming excess heat to mobilize resident air from typically non-sterile areas (floor & under the anaesthesia drape) into the surgical site, a finding that may have implications regarding surgical site sterility.

Perhaps the most striking finding within this study was the detection of hot-air convection currents originating from where the "mass-flow" of hot air exhausted the forced air warming blanket: for the hip arthroplasty with upper-body warming, this occurred under the anaesthesia drape by the mannequin's head; for the spinal implant with lower-body warming, this happened along the lower drape edge by the surgeon's feet. Further, the effects of these hot-air convection currents

This study compared the effects of excess waste heat released by two patient warming systems, CFW and FAW, on laminar OT ventilation performance during a mock knee

replacement surgery. FAW was found to release sufficient excess waste heat on the back-side of the surgical drape to elevate drape temperatures on the surgeon's side, which under certain clinical conditions created upward convection currents that compromised the laminar airflow protecting the surgical site from airborne contaminants. In contrast, CFW had no effect on drape temperatures or ventilation performance versus controls. Further, FAW waste heat established convection currents were shown to mobilize resident air from high pathogenic risk areas near the surgeon's feet into the surgical site, a finding that may have implications pertaining to SSI risks.

Perhaps the most striking finding within this study was the demonstrated sensitivity of the downward laminar airflow to even small changes in the OT environment. Placements of lights, personnel, or the surgical drape were all found to have profound effects on the pattern of air currents. In agreement with previous research observations,[10] "bubbles" depicted a large recirculation zone extending approximately a meter downstream from the surgical lights. Contaminants reaching this zone tended to remain suspended in a vortex for some period of time. The ability of this vortex to entrain contaminants was found to be further magnified when a clipped up drape was added to the system, since the drape created a "still zone" adjacent to this vortex by blocking the natural passage of the air out of the ventilation environment. Lastly, the addition of a surgeon near this "still zone" created a situation where even the slightest movements, ones that would not normally cause ventilation disruption, adversely affected the natural ventilation patterns.

As such, the detection of buoyancy driven convection currents in the "still zone" due to even moderate heating of the surgical drape's back side is neither surprising nor theoretically unsupported. With FAW and the drape clipped up, drape temperatures were found to be elevated (~5°C) in the "still zone" and, therefore, led to heating the quiescent air. "Bubbles" showed this heated quiescent air to move upwards along the drape edge facing the surgeon and in the process draw resident air from below the operative table upwards. This convection current system explains the 1000-fold increase in particle entrainment at the surgical site versus controls. Further, this phenomenon illustrates a mechanism that could, conceivably, result in the transport of large quantities

of resident floor level air into the surgical site. In contrast, CFW was not observed to elevate drape temperatures and, thus, had no effect on ventilation performance versus controls.

Interestingly, the effects of patient warming waste heat were found to be insignificant on ventilation performance when the drape was laid down. Dropping the drape created a new airflow channel that appeared to sweep the waste heat directly out of the ventilation environment over the patients head. However, this new airflow channel created added turbulence that lead to slight increases in particle entrainment within the surgical site when comparing control conditions. Further, removal of the drape may not be desirable for the drape is often applied to create a barrier between the surgical site and contaminants released from anesthesia related activities.

Nevertheless, the clinical relevance of this research relates to the possibility that excess patient warming waste heat either: 1) prevents the evacuation of airborne contaminants from the surgical site; and/or 2) mobilizes contaminant laden air from high risk areas, such as near the floor, into the surgical site. In terms of the former, this study was motivated, in part, by pilot research that detected longer contaminant residence times in the surgical site when FAW was used versus control. The results of this study confirm the rationale for such observations through the detection of a vortex over the surgical site. In terms of the latter (contaminant mobilization), free floating bacteria have a similar size distribution[11] (0.5 to 5.0μm) to that of the tracer employed in this study and, thus, the detection of floor level tracer in the surgical site suggests that waste heat generated convection currents could mobilize such pathogens. However, the ability of waste heat generated convection currents to mobilize larger fomites, such as shed skin cells[12] (typically larger than 5μm), is presently unknown. Thus, future research should be carried out to assess not only the movements of larger fomites, but also replicate the present study methods over a range of OT environments and surgical procedures to identify situations having a sensitivity to ventilation disruption.

The benefits of preventing surgical hypothermia are well established and form a critical component of a multi-faceted strategy to lessen the risks of surgical site infection[13,14] and improve surgical outcomes.[15,16] However, until the risks of waste heat contaminant mobilization can be fully evaluated, air-free patient warming systems are recommended as alternatives to FAW for contamination sensitive surgeries. Further, such air-free patient warming systems have been shown to be comparably effective to forced air warming in clinical trials.[17-24] Lastly, we are concerned with the results of a recent computational airflow study that fails to demonstrate the disruptive effects of waste heat on ventilation performance.[25] Studies of this methodology often employ overly simplistic models that do not represent the complexities of real surgical conditions and, therefore, will generally understate the seriousness of the risks.

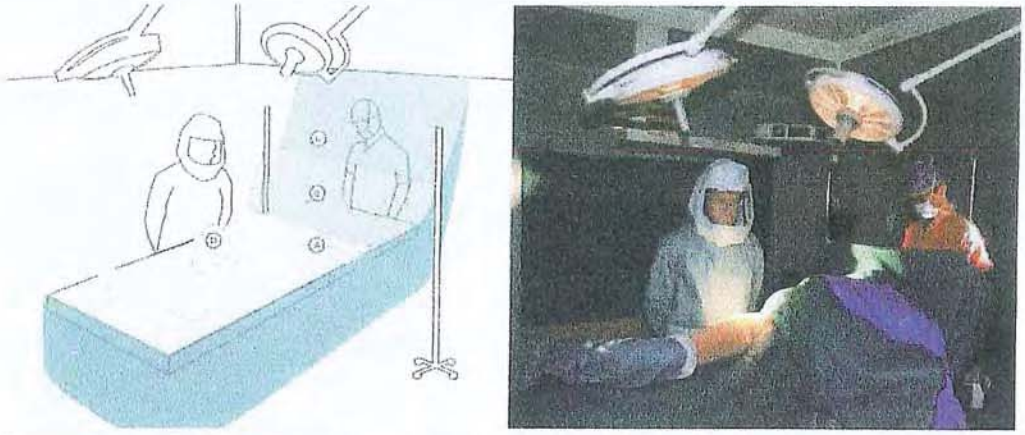

Figure 1: Hip arthroplasty setup with upper-body warming, showing: surgical drape positions of laid-down (A), half-drape (B), and full-drape (C) and surgical site location (D)

Figure 2: Lower lumbar spinal implant setup with lower-body warming and full-drape, showing: surgical site location (A).

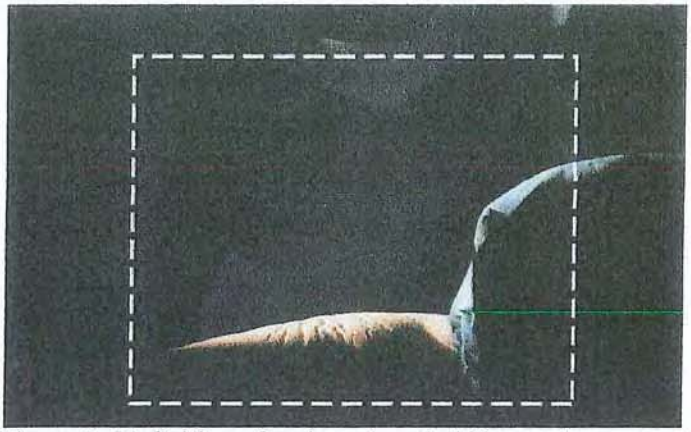

Figure 3: Definition of region where bubble counts were performed over the surgical site for hip arthroplasty with upper-body warming. Pictures shows bubbles (white steaks) appearing in the photograph for the experimental setup of forced air warming and half-drape.

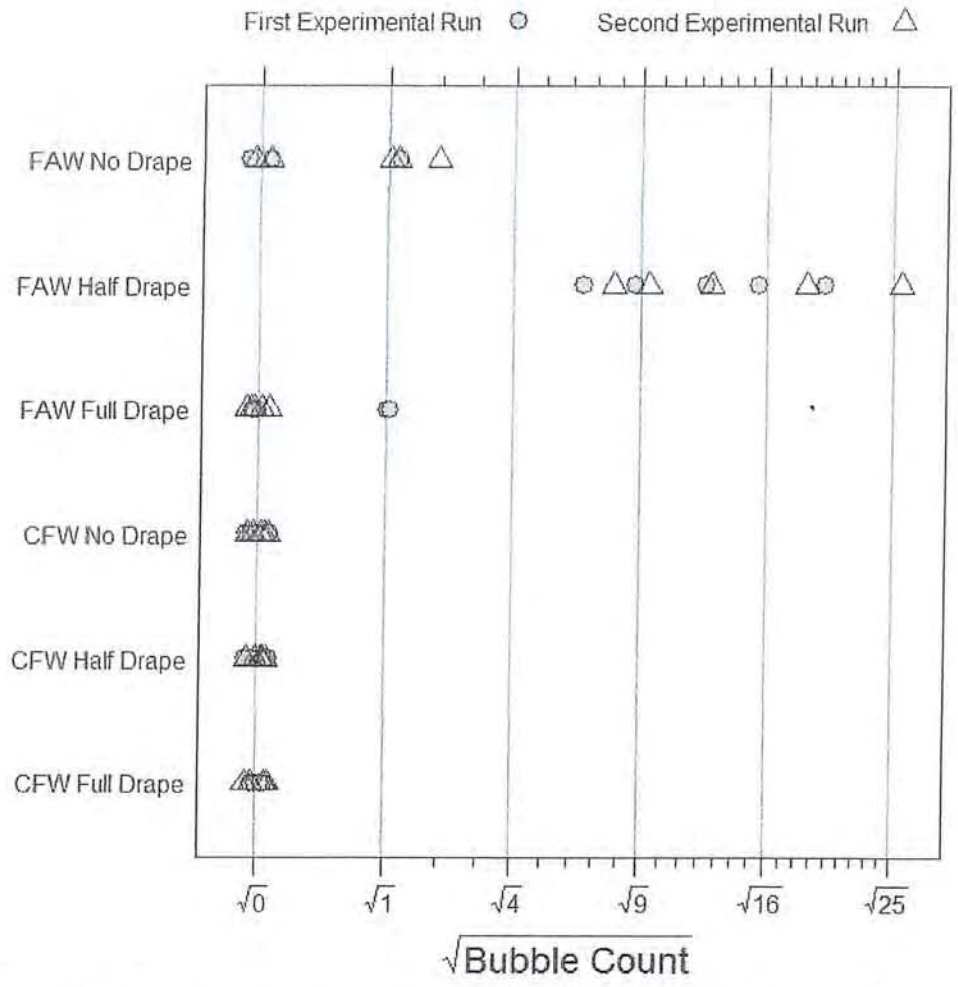

Figure 4: Bubble counts over the surgical site for each photograph. 5 photographs were taken for each experimental run. Abbreviations: FAW, Forced Air Warming; CFW, Conductive Fabric Warming.

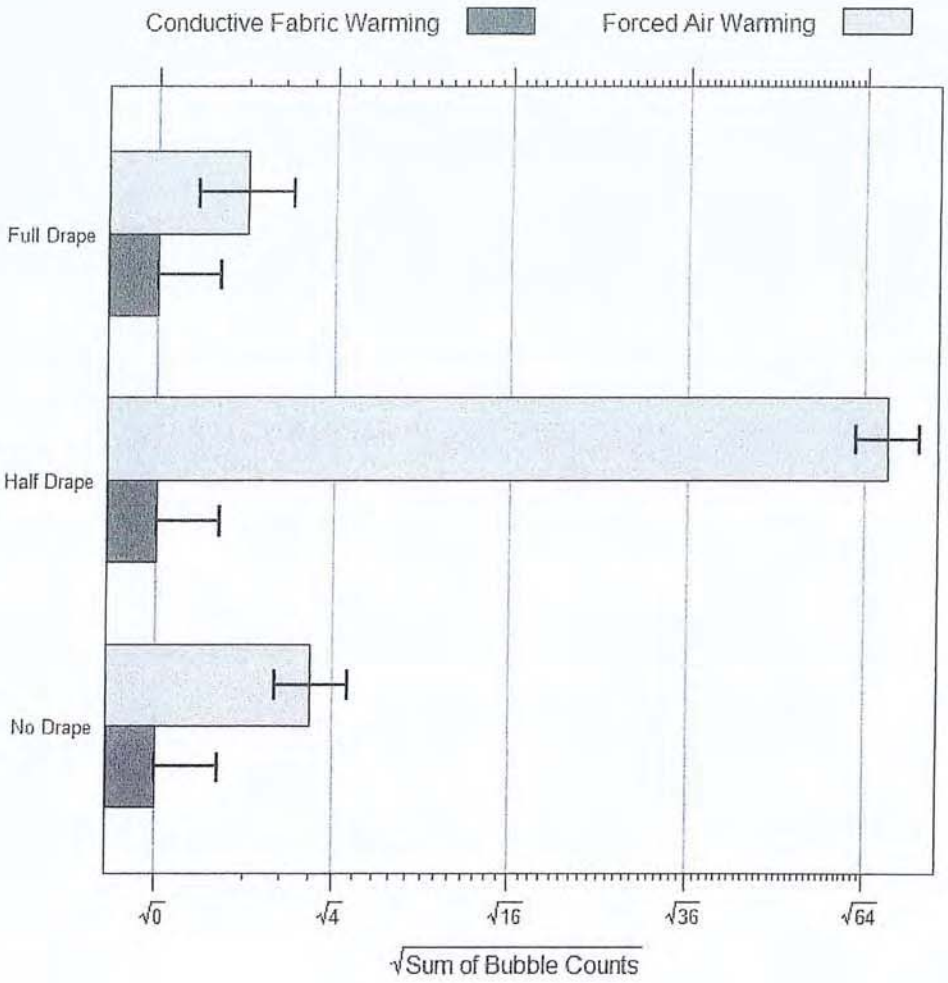

Figure 5: Average bubble count for experimental runs when the bubble counts are summed over the 5 photographs (±Standard Error of the Mean).

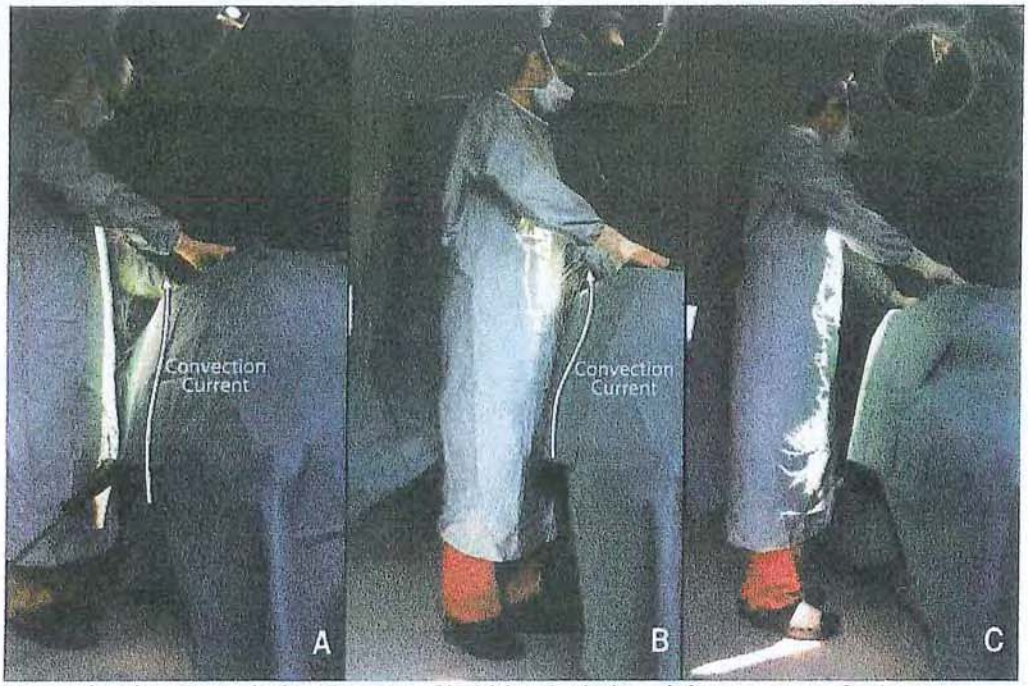

Figure 6: Time-lapsed-photography of bubbles depicting airflow patterns for lower lumbar spinal implant procedure with: (A & B) Forced air warming with resulting convection currents annotated and (C) conductive fabric warming.

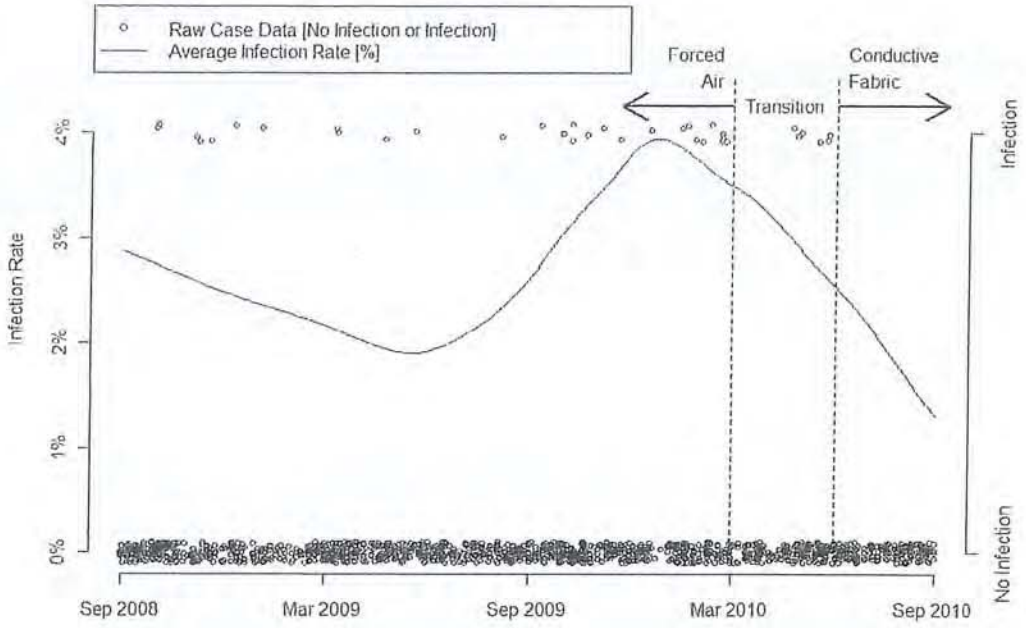

Figure 7: Infection data for n=1290 joint replacement cases with the outcome plotted on the right hand axis (data is jittered to avoid overprinting). A moving average of infection rate was plotted on the left hand axis. The change from forced air to conductive fabric patient warming in the orthopedic theaters is identified along with the transition period where both systems were used.

References

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Conflicts: Mike Reed reported no conflicts of interest

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Conflicts: Mark Albrecht worked for Augustine Biomedical + Design and received research funding from Augustine Biomedical + Design

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operations typically encountered: 1) a hip arthroplasty with upper-body warming, and 2) a lower lumbar spinal with lower-body warming. Ventilation airflow patterns were visualized using neutrally buoyant detergent bubbles and observational data on joint sepsis rates were compared for the period each warming device was in clinical use.

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Experimental Setup: Hip Arthroplasty

A mannequin was laid in the supine position on an operating table (Table Mfgr) and draped with a 3-piece orthopedic kit (Molnlycke Health Care) in accordance with standard protocols (**Fig 1**). A surgeon, dressed in occlusive clothing with head gear (MFGR), and an anesthesiologist stood motionless in front of the surgical site and behind the anesthesia screen. At the head of the operating table, the surgical drape was either: 1) clipped to the ceiling to create a barrier between the surgical site and anesthesia area (full-drape); 2) clipped to IV poles and raised 0.75 meters above the operating table (half-

drape); or 3) laid-down over the mannequin's head (laid-down). The experimental upper-body warming treatment was introduced under the drape and was either: 1) a torso forced air blanket (Bair Hugger Model 540, Arizant Healthcare, Eden Prairie, MN); or 2) a torso conductive fabric blanket (Hot Dog Model B110, Augustine Biomedical + Design, Eden Prairie, MN). The blankets were powered by standard controllers (conductive fabric - Model WC02, Augustine Biomedical + Design; forced air - Model 750, Arizant Healthcare). "Bubbles" were introduced at the neck of the mannequin to track under-drape resident air movements in the region where the excess patient warming heat was being released.

Experimental Setup: Lower lumbar spinal

The same mannequin was laid in the prone position on the operating table and four drapes were arranged in a "square" configuration (MFGR) with the anesthesia screen at full-height in accordance with standard protocols (**Fig 2**). A single surgeon stood motionless next to the surgical site for all experiments. The experimental lower-body warming treatment was introduced under the drape and was either: 1) a lower-body forced air blanket (Bair Hugger Model 525, Arizant Healthcare); or 2) a lower-body conductive fabric blanket (Hot Dog Model B103, Augustine Biomedical + Design). The blankets were powered by the same controllers as listed above. "Bubbles" were introduced at floor level between the surgeon's body and the operating room table in the region where the patient warming excess heat was being released.

Sampling Procedures

Hip Arthroplasty: Bubble counts over the surgical site were measured for each experimental treatment using a sequence of 5 photographs taken at 10 second intervals. The number of bubbles reaching the surgical site was determined by counting the number of bubbles in a 0.5 by 0.5 meter region over the surgical site in each photograph (**Fig 3**).
Lower Lumbar Spinal: Time-lapsed-photography was chosen over the use of bubble counts to show differences in ventilation performance between patient warming systems given the significant change in observed surgical site airflow patterns (see **Results**).

Experimental Design

Hip Arthroplasty: A replicated (n=2) $3^1 2^1$ full factorial design was employed to assess changes in bubble counts over the surgical site. The experimental factors considered were: 1) anesthesia screen: laid-down, half-screen, or full-screen; and 2) patient warming device: conductive fabric or forced air.

Lower Lumbar Spinal: No design was employed or necessary to demonstrate the difference in ventilation performance between forced air and conductive fabric patient warming systems (see **Results**).

Statistical Analysis

A Poisson regression model was fitted to the hip arthroplasty data having the sum of bubble counts for each experimental run (5 pictures) as the response and the two factors identified in the experimental design as predictors (including interaction). Reported values are predicted means (± standard error of the mean) for experimental factor combinations based upon maximum likelihood estimates. Wald tests were used for significance.

Joint Sepsis Data

Joint sepsis data was collected for all orthopedic operations performed at the hospital during the 2-year period prior to the study, with dates comprising 9/1/2008 to 9/1/2010. A transition in patient warming systems from forced air to conductive fabric was made in all four orthopedic theaters starting 3/1/2010 and ending 6/1/2010.

Results

Hip Arthroplasty:

The number of bubbles reaching the surgical site measured the degree to which patient warming excess heat mobilized resident under-drape air over the anesthesia screen and into the surgical site. Bubble counts per photograph (**Fig 4**) suggest that forced air warming generated sufficient excess heat to mobilize resident under-drape air over the anesthesia screen. In contrast, conductive fabric warming did not generate sufficient excess heat to have the same mobilizing effect. Further, surgical drape position appeared to have a large effect on resident under-drape air mobilization into the surgical site for forced air warming, with the half-drape configuration resulting in the largest degree of resident-air mobilization.

Differences in the sum of bubble counts for each experimental run (**Fig 5**) were significant between conductive fabric and forced air warming for the drape configurations of half-drape (0 versus 68, $p<0.001$) and laid-down (0 versus 3, $p=0.010$); differences for full-drape (0 versus 1, $p=0.283$) were insignificant. It was necessary to model the sum of bubble counts for statistical inference; otherwise observations would not be independent.

Lower Lumbar Spinal:

Time-lapsed-photography showed forced air warming excess heat to generate hot-air convection currents that transported large quantities of floor-level resident air upwards and into the surgical site (**Fig 6**). These convection currents appeared to form in the space between the surgeon's body and the operating room table. In contrast, conductive fabric warming did not generate sufficient excess heat to establish such convection currents. Instead, with conductive fabric warming ventilation airflow patterns followed the intended path - downwards and away from the surgical site.

Joint Sepsis Rates:

A 2-year observation of orthopedic infections revealed a reduction in joint sepsis rates for the period conductive fabric warming was in clinical use versus forced air warming, with

average infection rates of 0.0% (n=161) versus 3.0% (n=936), respectively (**Fig 7**). There was a 3 month transition period where both patient warming devices were used in the orthopedic theaters.

Discussion

This study compared the effects of two patient warming systems, forced air and conductive fabric, on ventilation performance in an ultra-clean operating theater during spinal and orthopedic procedures. Forced air warming excess heat was found to generate convection currents that disrupted clean-airflow patterns over the surgical site during both procedures. In contrast, conductive fabric warming released minimal excess heat and was shown to have no effect on ventilation performance in either procedure. The results also showed forced air warming excess heat to mobilize resident air from typically non-sterile areas (floor & under the anesthesia drape) into the surgical site, a finding that may have implications regarding surgical site sterility.

Perhaps the most striking finding was the detection of hot-air convection currents originating from where the "mass-flow" of hot air exhausted the forced air warming blanket: for the hip arthroplasty with upper-body warming, convection currents formed near the mannequin's head; for the spinal implant with lower-body warming, convection currents formed along the lower drape edge by the surgeon's legs. The formation of such convection currents may, at first, appear to be theoretically unsupported since forced air warming exhausts a heated airflow of only 40 cubic feet per minute into a ventilation environment having an airflow of 6000 cubic feet per minute. However, one must also consider the effects of surgical lighting, drapes, and personnel on ventilation performance, all of which create localized airflow disturbances that aid in convection current formation.

Prior research in ultra-clean ventilation theaters has shown surgical lighting to be a significant source of ventilation disruption through the downstream wake and associated recirculation zone. In our study, the use of "bubbles" allowed us to visualize this recirculation zone, which was found to extend about 1 meter below the body of each

surgical light. "Bubbles" and, thus, resident air reaching this zone tended to remain suspended in this vortex for some time. The presence of a raised anesthesia drape was shown to further magnify the size and effect of this vortex, for the drape blocked the natural passage of air out of the ventilation field and created a "still zone" adjacent to the vortex. Lastly, the presence of a surgeon or anesthesiologist near this "still zone" created an additional ventilation flow blockage resulting in a situation where even the slightest movements, ones that would not normally cause ventilation disruption, adversely impacted the natural airflow patterns over the surgical site.

Under these fragile conditions, the "mass-flow" of hot forced air warming exhaust was sufficiently buoyant to push upwards within these locally compromised ventilation regions. For the hip arthroplasty, the compromised region was along the backside of the anesthesia drape. For the lower lumbar spinal implant, the compromised region was the channel between the surgeon's body and operating table. Both compromised regions resulted from a combination of lights, drapes, and personnel forming a pocket having the following characteristics: the pocket 1) was sheltered from the downward ventilation airflows; 2) extended into the region where the "mass-flow" of forced air warming exhaust was being vented; and, 3) formed a path that terminated near the surgical site. Due to the reduced ventilation velocity within the pocket, hot-air convection currents were able to form and resulted in the transport of floor-level and under-drape air into the surgical site.

The clinical concern regarding the formation of such convection currents is two-fold. First, these currents oppose the natural clean-airflow patterns that are intended to sweep contaminants down and away from the surgical site. Thus, contaminants released in the vicinity of the surgical site are less likely to be cleared. Second, the upward mobilization of floor-level and under-drape air could potentially compromise the sterility of the surgical site, since resident air from these locations is typically laden with pathogens shed from the surgical staff. Further, even small elevations in contaminant exposure could be of clinical significance given that airborne derived infection risks are exponentially magnified with implantable procedures. Empirical support for the concept that observed

convection currents resulted in increased surgical site contaminant exposure can be found in the observed reduction in hospital arthroplasty infection rates when a switch from forced air to conductive fabric warming was implemented. However, this infection data is observational in nature and does not prove that such a relationship exists since we were unable to control for other infection reduction measures instituted by the hospital over the 2-year period.

Further, the present study is somewhat limited in that we assessed the movements of "bubbles" as a surrogate for the movement of pathogenic contaminants. Thus, the clinical relevance of our findings depend on two assumptions: 1) that floor-level and under-drape air is non-sterile; and 2) that airborne contaminant concentrations from these locations represent a significant infection risk relative to other contamination sources. Moreover, the entire field of prior research assessing forced air warming excess heat and changes in airborne pathogen levels during implantable procedures is limited to a single orthopedic study, in which forced air warming resulted in elevated microbial counts over the surgical site. However, the contamination increase was deemed to be far less than that resulting from personnel movements and such increases did not exceed recommended bacterial levels. Yet, it is unknown how these results translate over the range of implantable procedures. Even minor differences in factors such as surgical draping, procedural practices, and theater dress are likely to have large effects on both floor-level and under-drape contaminant levels and the dynamics of convection current formation.

Until the effects of forced air warming excess heat on ventilation disruption can be fully evaluated in regards to affecting the sterility of the surgical site, the use of air-free patient warming alternatives might be recommended for implant procedures carried out in ultra-clean theaters.

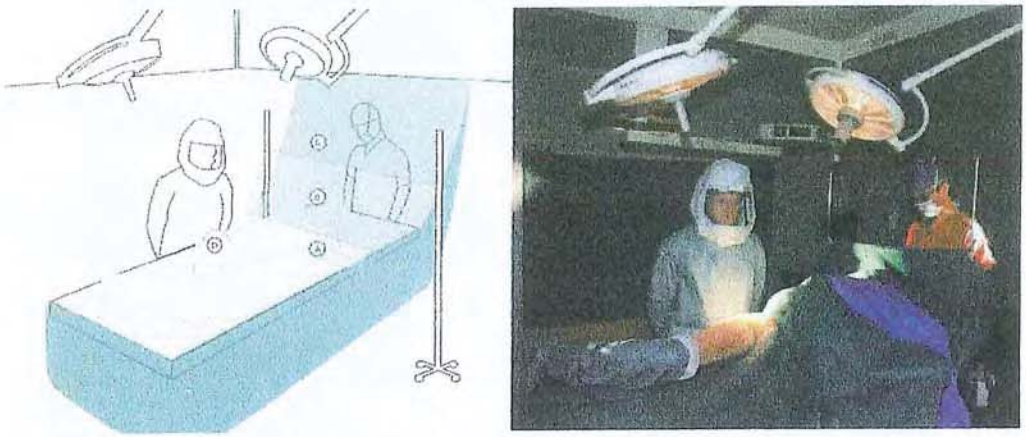

Figure 1: Hip arthroplasty setup with upper-body warming, showing: surgical drape positions of laid-down (A), half-drape (B), and full-drape (C) and surgical site location (D)

Figure 2: Lower lumbar spinal implant setup with lower-body warming and full-drape, showing: surgical site location (A).

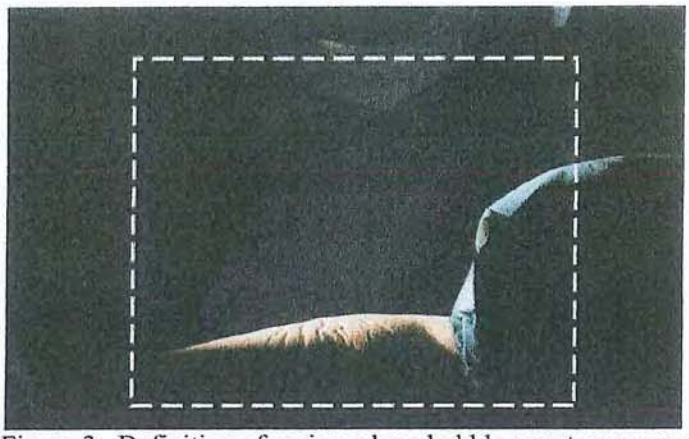

Figure 3: Definition of region where bubble counts were performed over the surgical site for hip arthroplasty with upper-body warming. A picture shows bubbles (white steaks) appearing in the photograph for the experimental setup of forced air warming and half-drape.

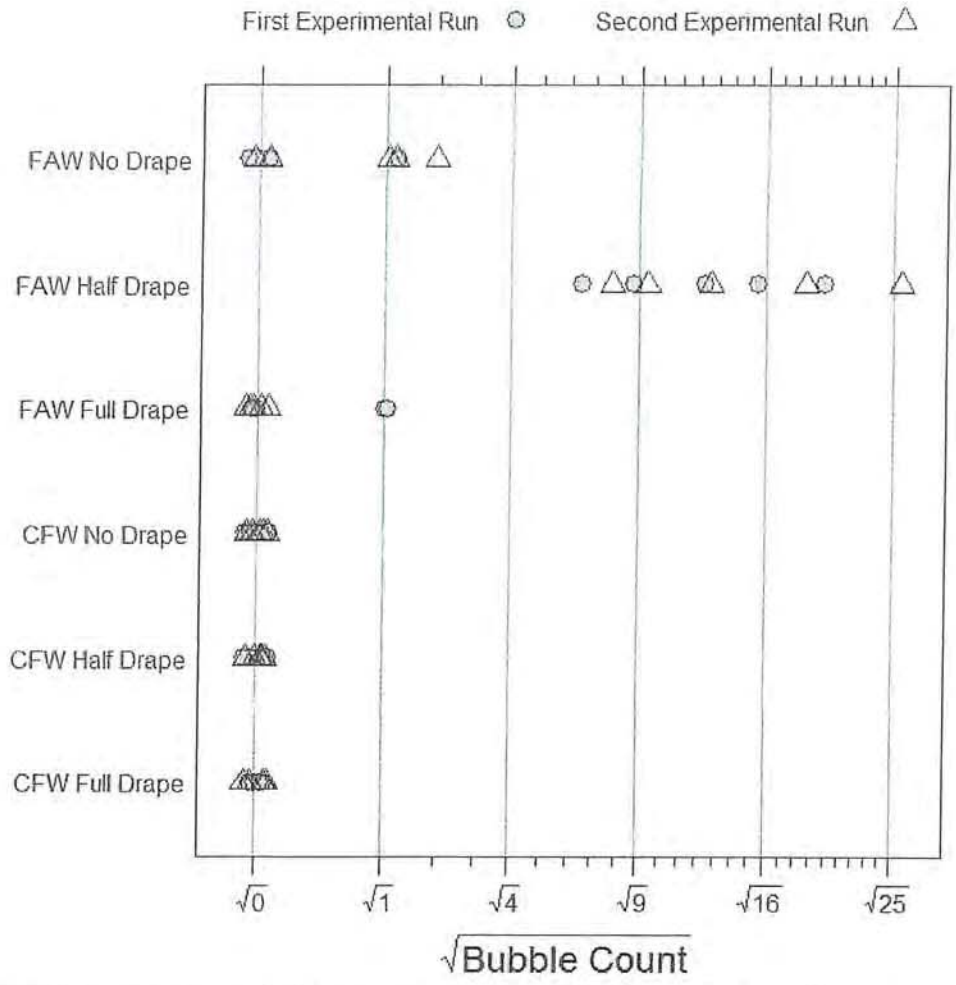

Figure 4: Bubble counts over the surgical site for each photograph. 5 photographs were taken for each experimental run. Abbreviations: FAW, Forced Air Warming; CFW, Conductive Fabric Warming.

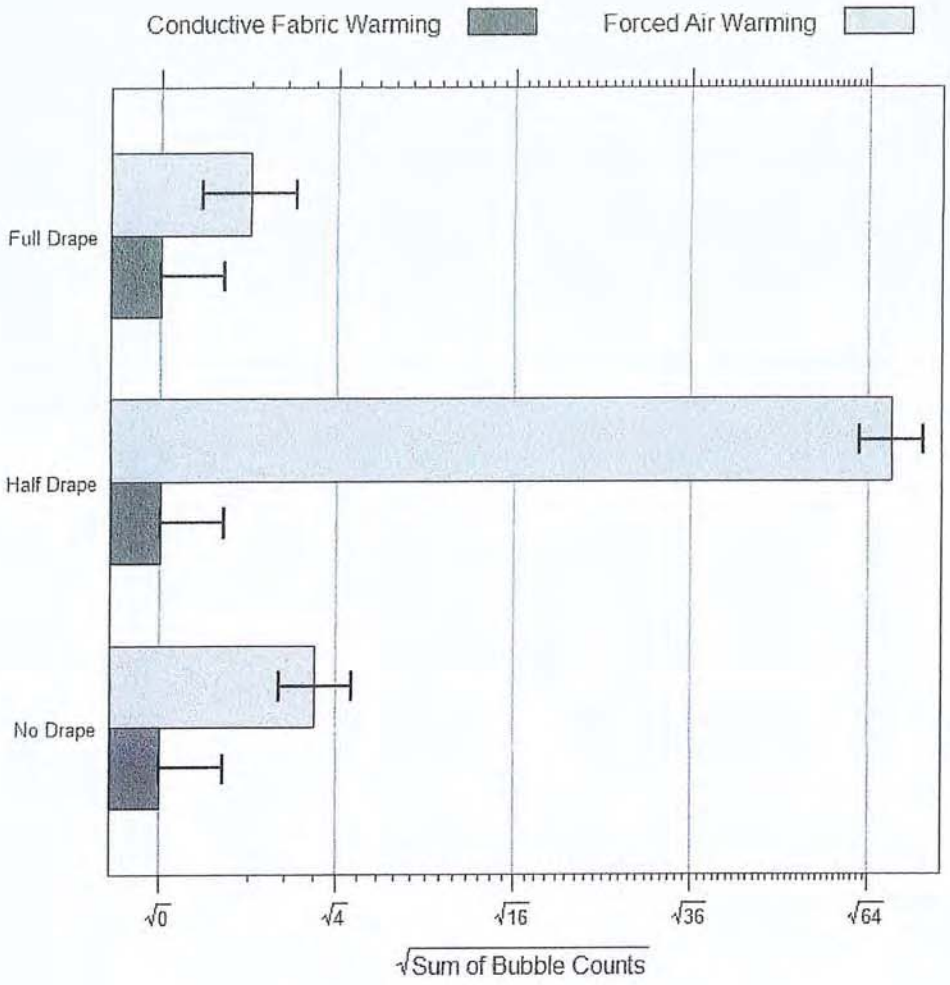

Figure 5: Average bubble count for experimental runs when the bubble counts are summed over the 5 photographs (±Standard Error of the Mean).

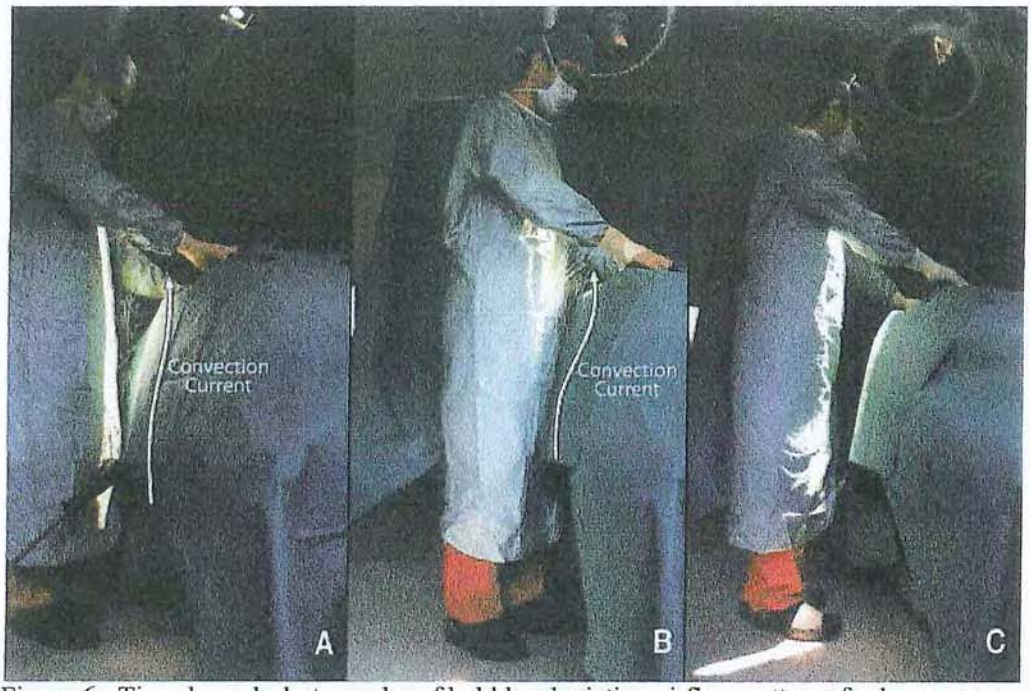

Figure 6: Time-lapsed-photography of bubbles depicting airflow patterns for lower lumbar spinal implant procedure with: (A & B) Forced air warming with resulting convection currents annotated and (C) conductive fabric warming.

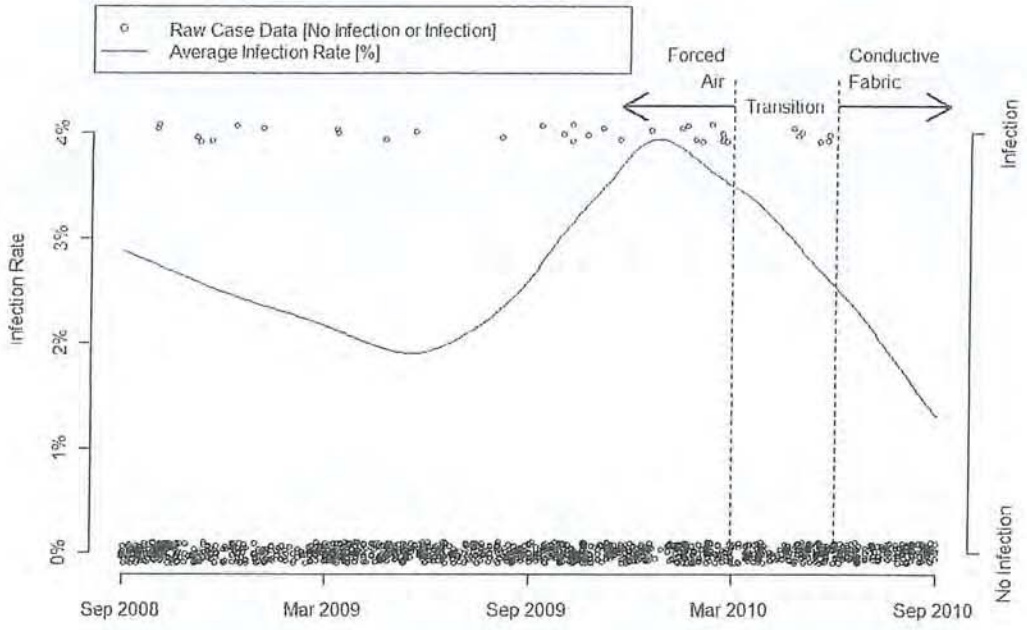

Figure 7: Infection data for n=1290 joint replacement cases with the outcome plotted on the right hand axis (data is jittered to avoid overprinting). A moving average of infection rate was plotted on the left hand axis. The change from forced air to conductive fabric patient warming in the orthopedic theaters is identified along with the transition period where both systems were used.

References

Document Name: Manuscript_Reed_3.pdf

Abstract

Introduction: Ultra-clean ventilation is designed to protect the surgical site from airborne pathogens. However, ventilation performance is fragile and depends critically on airflow volumes and temperature gradients. Patient warming systems represent a disruption risk via the excess heat they release. Therefore, we compared the effects of two patient warming systems – (1) conductive fabric and (2) forced air – on clean-airflow patterns over the surgical site during orthopedic and spinal implant procedures.

Methods: A mannequin was draped for (1) a hip prosthesis and (2) a lower lumbar spinal implant in a partial-walled ultra-clean theater. Neutral buoyancy detergent bubbles were released under the anesthesia drape and at floor level to visualize air-currents and assess the mobilization of resident air into the clean-airflow over the surgical site. For the hip prosthesis, a randomized design assessed the effects upper-body warming system and anesthesia drape height on bubbles reaching the surgical site. For the spinal, the effect of lower-body warming system was assessed with time-lapsed-photography of bubbles. Lastly, joint sepsis rates were tracked for a 2 year period over which a change from forced air to conductive fabric was implemented.

Results: For the hip prosthesis, bubble counts were significantly higher for forced air than conductive fabric for laid-down (3 versus 0; $p=0.010$) and half-height (68 versus 0; $p<0.001$) anesthesia draping; differences for full-height draping were insignificant (1 versus 0; $p=0.283$). For the spinal, time-lapsed-photography showed forced air to establish upwards convection currents that transported floor air into the surgical site; this convection current was not present with conductive fabric. Joint sepsis infection rates were reduced after the implementation of conductive fabric warming (0% for $n=161$) versus prior rates with forced air (3.0% for $n=936$).

Conclusion: Excess heat from forced air warming disrupted clean-airflow patterns over the surgical site and generated upward convection currents, which transported non-sterile air from the floor and the anesthesia side of the drape into the surgical site; conductive fabric warming had no such effects. Observation of joint sepsis rates suggests an empirical reduction in infection with conductive fabric warming in orthopedics.

Number of words: 339

Forced Air Warming and Ultra-Clean Ventilation Do Not Mix: The effect of excess vented heat on clean-airflow patterns.

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Results: For the hip prosthesis, bubble counts were significantly higher for forced air than conductive fabric for laid-down (3 versus 0; $p=0.010$) and half-height (68 versus 0; $p<0.001$) anesthesia draping; differences for full-height draping were insignificant (1 versus 0; $p=0.283$). For the spinal, time-lapsed-photography showed forced air to establish upwards convection currents that transported floor air into the surgical site; this convection current was not present with conductive fabric. Joint sepsis infection rates were reduced after the implementation of conductive fabric warming (0% for $n=161$) versus prior rates with forced air (3.0% for $n=936$).

Conclusion: Excess heat from forced air warming disrupted clean-airflow patterns over the surgical site and generated upward convection currents, which transported non-sterile air from the floor and the anesthesia side of the drape into the surgical site; conductive fabric warming had no such effects. Observation of joint sepsis rates suggests an empirical reduction in infection with conductive fabric warming in orthopedics.

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Introduction

Although most famously remembered for pioneering the hip arthroplasty, Sir John Charnley was among the first to recognize the critical role of operating theater (OT) ventilation in preventing joint sepsis. Charnley postulated that the "surgical implant might provide a nidus for the growth of airborne bacteria which ordinarily are accepted as non-pathogenic." Research efforts confirmed Charnley's insights through animal studies and a national clinical trial involving over 8000 operations that demonstrated the efficacy of clean air for the reduction of arthroplasty infection rates. As such, ultra-clean ventilation became the standard for orthopedic procedures. Ultra-clean ventilation protects the surgical site from airborne contamination through the constant delivery of a downward uniform velocity (0.3 to 0.5 m/s) highly filtered (>99.997%) airflow. However, the performance of ultra-clean ventilation depends critically on air-flow volumes and proper temperature gradients, the latter of which may be disrupted by excess heat released from patient warming devices.

The vented airflow from forced air warming is released at 43°C, which is often 20°C above ambient OT conditions. The release of such thermal energy has the potential to establish temperature gradients that impede the downward velocity of the OT ventilation airflows. Further, reductions in downward flow velocity have been shown to increase contaminant entrainment into the surgical site. Moreover, the release of excess heat may generate convection currents that rise against the downward airflows and mobilize non-sterile floor-level air into the surgical site.

Air-free alternatives, such as conductive fabric warming, have been developed that are comparably effective to forced air for the prevention of surgical hypothermia. These alternatives have much higher thermal efficiencies than forced air warming and, therefore, release only a fraction of the excess heat. As such, there is a need to critically assess the impact of forced air warming versus air-free alternatives on ultra-clean ventilation performance. Specifically, we compared the effects of (1) conductive fabric and (2) forced air warming on clean-airflow patterns over the surgical site in a partial-walled ultra-clean OT during two procedures representing the variety of implantable

operations typically encountered: 1) a hip arthroplasty with upper-body warming, and 2) a lower lumbar spinal with lower-body warming. Ventilation airflow patterns were visualized using neutrally buoyant detergent bubbles and observational data on joint sepsis rates were compared for the period each warming device was in clinical use.

Methods

Ultra-Clean Operating Theater Characteristics:

Experiments were carried out in a partial-walled ultra-clean OT (ExFlow 90, Howorth, United Kingdom) used for orthopedic and spinal surgery at Wansbeck Hospital (Ashington, United Kingdom). Validation and verification checks per HTM 2025 showed the OT airflows to be within specification and having a mean velocity of 0.44 m/s two-meters off the floor, which is above the threshold required by the standards (0.38 m/s). However, a slight airflow imbalance was detected during validation testing due to the location of the theater prep room that affected the results of a single particle entrainment test; entrainment values were 12% at that location, which marginally exceeded the recommended threshold of 10%. This slight discrepancy was unlikely to have any effect on the results of the study. Further, smoke testing detected normal airflow patterns under the canopy and the OT passed microbial contamination testing.

Airflow Visualization Procedures:

High intensity lighting was used to illuminate neutrally buoyant detergent bubbles having a 4 mm average diameter (referred to herein as "bubbles"). "Bubbles" were produced by a bubble generator (Sage Action, Ithaca, NY), which utilized a helium-mixed air supply, detergent, and centripetal bubble size classification filter. The bubble generator is specifically designed and validated for the visualization of air currents. For photography, a digital camera (D300, Nikon, Melville, NY) was employed and shutter exposure time was set to ¼ of a second for time-lapsed-photography.

Experimental Setup: Hip Arthroplasty

A mannequin was laid in the supine position on an operating table (Table Mfgr) and draped with a 3-piece orthopedic kit (Molnlycke Health Care) in accordance with standard protocols (**Fig 1**). A surgeon, dressed in occlusive clothing with head gear (MFGR), and an anesthesiologist stood motionless in front of the surgical site and behind the anesthesia screen. At the head of the operating table, the surgical drape was either: 1) clipped to the ceiling to create a barrier between the surgical site and anesthesia area (full-drape); 2) clipped to IV poles and raised 0.75 meters above the operating table (half-

drape); or 3) laid-down over the mannequin's head (laid-down). The experimental upper-body warming treatment was introduced under the drape and was either: 1) a torso forced air blanket (Bair Hugger Model 540, Arizant Healthcare, Eden Prairie, MN); or 2) a torso conductive fabric blanket (Hot Dog Model B110, Augustine Biomedical + Design, Eden Prairie, MN). The blankets were powered by standard controllers (conductive fabric - Model WC02, Augustine Biomedical + Design; forced air - Model 750, Arizant Healthcare). "Bubbles" were introduced at the neck of the mannequin to track under-drape resident air movements in the region where the excess patient warming heat was being released.

Experimental Setup: Lower lumbar spinal

The same mannequin was laid in the prone position on the operating table and four drapes were arranged in a "square" configuration (MFGR) with the anesthesia screen at full-height in accordance with standard protocols (**Fig 2**). A single surgeon stood motionless next to the surgical site for all experiments. The experimental lower-body warming treatment was introduced under the drape and was either: 1) a lower-body forced air blanket (Bair Hugger Model 525, Arizant Healthcare); or 2) a lower-body conductive fabric blanket (Hot Dog Model B103, Augustine Biomedical + Design). The blankets were powered by the same controllers as listed above. "Bubbles" were introduced at floor level between the surgeon's body and the operating room table in the region where the patient warming excess heat was being released.

Sampling Procedures

Hip Arthroplasty: Bubble counts over the surgical site were measured for each experimental treatment using a sequence of 5 photographs taken at 10 second intervals. The number of bubbles reaching the surgical site was determined by counting the number of bubbles in a 0.5 by 0.5 meter region over the surgical site in each photograph (**Fig 3**).
Lower Lumbar Spinal: Time-lapsed-photography was chosen over the use of bubble counts to show differences in ventilation performance between patient warming systems given the significant change in observed surgical site airflow patterns (see **Results**).

Experimental Design

Hip Arthroplasty: A replicated (n=2) $3^1 2^1$ full factorial design was employed to assess changes in bubble counts over the surgical site. The experimental factors considered were: 1) anesthesia screen: laid-down, half-screen, or full-screen; and 2) patient warming device: conductive fabric or forced air.

Lower Lumbar Spinal: No design was employed or necessary to demonstrate the difference in ventilation performance between forced air and conductive fabric patient warming systems (see **Results**).

Joint Sepsis Data

Joint sepsis data was collected for all orthopedic operations performed at the hospital during the 2-year period prior to the study, with dates comprising 9/1/2008 to 9/1/2010. A transition in patient warming systems from forced air to conductive fabric was made in all four orthopedic theaters starting 3/1/2010 and ending 6/1/2010.

Statistical Analysis

A Poisson regression model was fitted to the hip arthroplasty data having the sum of bubble counts for each experimental run (5 pictures) as the response and the two factors identified in the experimental design as predictors (including interaction). Reported values are predicted means (± standard error of the mean) for experimental factor combinations. Wald tests were used for significance.

A logistic regression model was fitted to the joint sepsis data having infection as the response and the period (forced air, transition, and conductive fabric warming) as predictors. Reported values are predicted mean infection rates (± standard error of the mean) for each period. Wald tests were used for significance.

Results

Hip Arthroplasty:

The number of bubbles reaching the surgical site measured the degree to which patient warming excess heat mobilized resident under-drape air over the anesthesia screen and into the surgical site. Bubble counts per photograph (**Fig 4**) suggest that forced air warming generated sufficient excess heat to mobilize resident under-drape air over the anesthesia screen. In contrast, conductive fabric warming did not generate sufficient excess heat to have the same mobilizing effect. Further, surgical drape position appeared to have a large effect on resident under-drape air mobilization into the surgical site for forced air warming, with the half-drape configuration resulting in the largest degree of resident-air mobilization.

Differences in the sum of bubble counts for each experimental run (**Fig 5**) were significant between conductive fabric and forced air warming for the drape configurations of half-drape (0 versus 68, $p<0.001$) and laid-down (0 versus 3, $p=0.010$); differences for full-drape (0 versus 1, $p=0.283$) were insignificant. It was necessary to model the sum of bubble counts for statistical inference; otherwise observations would not be independent.

Lower Lumbar Spinal:

Time-lapsed-photography showed forced air warming excess heat to generate hot-air convection currents that transported large quantities of floor-level resident air upwards and into the surgical site (**Fig 6**). These convection currents appeared to form in the space between the surgeon's body and the operating room table. In contrast, conductive fabric warming did not generate sufficient excess heat to establish such convection currents. Instead, with conductive fabric warming ventilation airflow patterns followed the intended path - downwards and away from the surgical site.

Joint Sepsis Rates:

A 2-year observation of orthopedic infections revealed a significant reduction in joint sepsis rates for the period conductive fabric warming was in clinical use versus forced air

warming, with average infection rates of 0.0% (n=165) versus 3.0% (n=965), respectively (**Fig 7**). An exact p-value cannot be calculated for this comparison given that there were no infections during the conductive fabric warming period. There was a 3 month transition period where both patient warming devices were used in the orthopedic theaters having an infection rate of 3.7% (n=160), which was not significantly different from the infection rate of 3.0% during the forced air warming period (p=0.62).

Discussion

This study compared the effects of two patient warming systems, forced air and conductive fabric, on ventilation performance in an ultra-clean operating theater during spinal and orthopedic procedures. Forced air warming excess heat was found to generate convection currents that disrupted clean-airflow patterns over the surgical site during both procedures. In contrast, conductive fabric warming released minimal excess heat and was shown to have no effect on ventilation performance in either procedure. The results also showed forced air warming excess heat to mobilize resident air from typically non-sterile areas (floor & under the anesthesia drape) into the surgical site, a finding that may have implications regarding surgical site sterility.

Perhaps the most striking finding was the detection of hot-air convection currents originating from where the "mass-flow" of hot air exhausted the forced air warming blanket: for the hip arthroplasty with upper-body warming, convection currents formed near the mannequin's head; for the spinal implant with lower-body warming, convection currents formed along the lower drape edge by the surgeon's legs. The formation of such convection currents may, at first, appear to be theoretically unsupported since forced air warming exhausts a heated airflow of only 40 cubic feet per minute into a ventilation environment having an airflow of 6000 cubic feet per minute. However, one must also consider the effects of surgical lighting, drapes, and personnel on ventilation performance, all of which create localized airflow disturbances that aid in convection current formation.

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Under these fragile conditions, the "mass-flow" of hot forced air warming exhaust was sufficiently buoyant to push upwards within these locally compromised ventilation regions. For the hip arthroplasty, the compromised region was along the backside of the anesthesia drape. For the lower lumbar spinal implant, the compromised region was the channel between the surgeon's body and operating table. Both compromised regions resulted from a combination of lights, drapes, and personnel forming a pocket having the following characteristics: the pocket 1) was sheltered from the downward ventilation airflows; 2) extended into the region where the "mass-flow" of forced air warming exhaust was being vented; and, 3) formed a path that terminated near the surgical site. Due to the reduced ventilation velocity within the pocket, hot-air convection currents were able to form and resulted in the transport of floor-level and under-drape air into the surgical site.

The clinical concern regarding the formation of such convection currents is two-fold. First, these currents oppose the natural clean-airflow patterns that are intended to sweep contaminants down and away from the surgical site. Thus, contaminants released in the vicinity of the surgical site are less likely to be cleared. Second, the upward mobilization of floor-level and under-drape air could potentially compromise the sterility of the

surgical site, since resident air from these locations is typically laden with pathogens shed from the surgical staff. Further, even small elevations in contaminant exposure could be of clinical significance given that airborne derived infection risks are exponentially magnified with implantable procedures. Empirical support for the concept that observed convection currents resulted in increased surgical site contaminant exposure can be found in the observed reduction in hospital arthroplasty infection rates when a switch from forced air to conductive fabric warming was implemented. However, this infection data is observational in nature and does not prove that such a relationship exists since we were unable to control for other infection reduction measures instituted by the hospital over the 2-year period.

Further, the present study is somewhat limited in that we assessed the movements of "bubbles" as a surrogate for the movement of pathogenic contaminants. Thus, the clinical relevance of our findings depend on two assumptions: 1) that floor-level and under-drape air is non-sterile; and 2) that airborne contaminant concentrations from these locations represent a significant infection risk relative to other contamination sources. Moreover, the entire field of prior research assessing forced air warming excess heat and changes in airborne pathogen levels during implantable procedures is limited to a single orthopedic study, in which forced air warming resulted in elevated microbial counts over the surgical site. However, the contamination increase was deemed to be far less than that resulting from personnel movements and such increases did not exceed recommended bacterial levels. Yet, it is unknown how these results translate over the range of implantable procedures. Even minor differences in factors such as surgical draping, procedural practices, and theater dress are likely to have large effects on both floor-level and under-drape contaminant levels and the dynamics of convection current formation.

Until the effects of forced air warming excess heat on ventilation disruption can be fully evaluated in regards to affecting the sterility of the surgical site, the use of air-free patient warming alternatives might be recommended for implant procedures carried out in ultra-clean theaters.

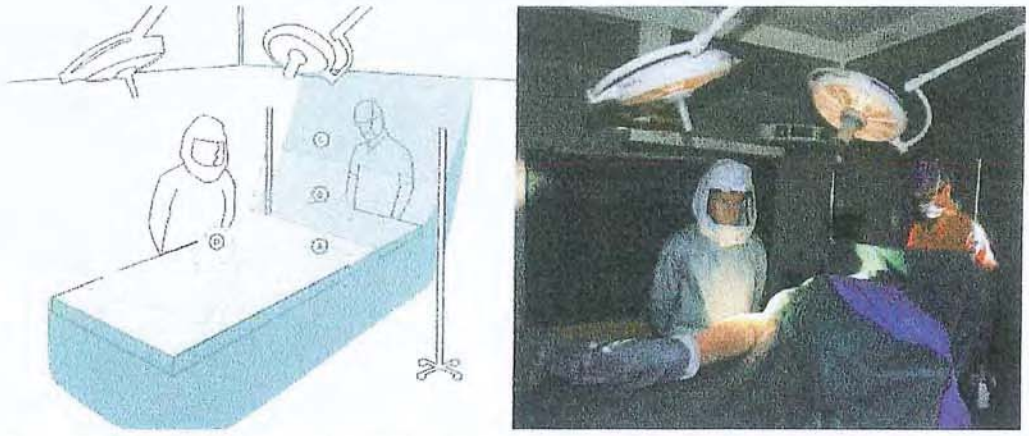
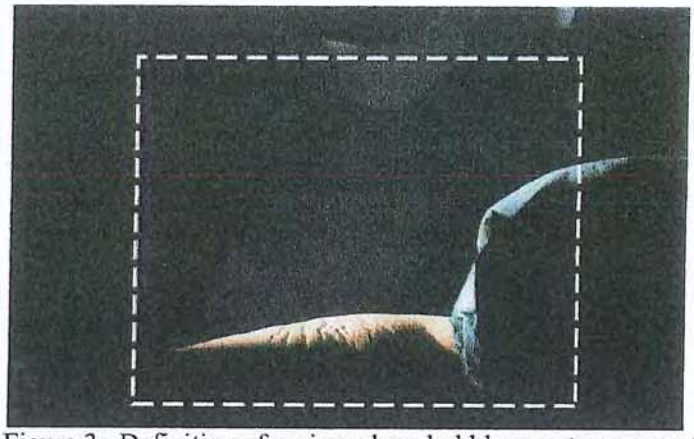


Figure 1: Hip arthroplasty setup with upper-body warming, showing: surgical drape positions of laid-down (A), half-drape (B), and full-drape (C) and surgical site location (D)

Figure 2: Lower lumbar spinal implant setup with lower-body warming and full-drape, showing: surgical site location (A).



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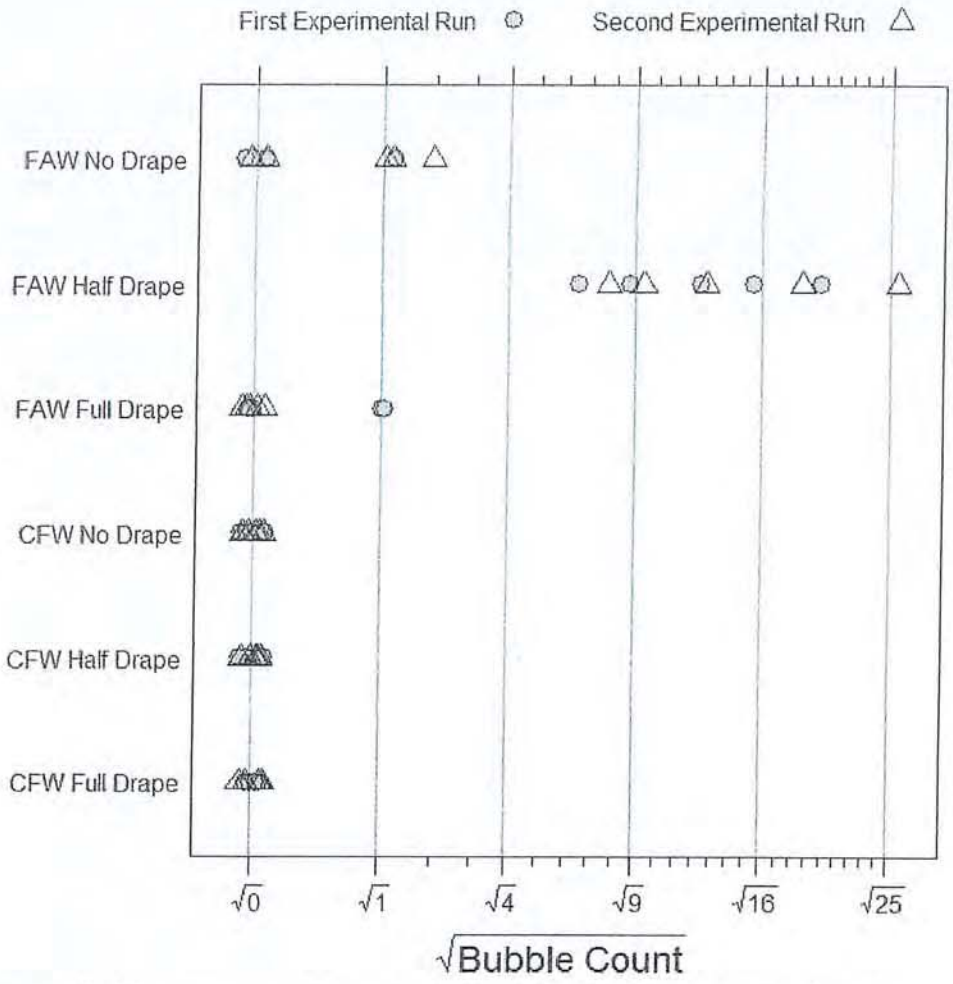

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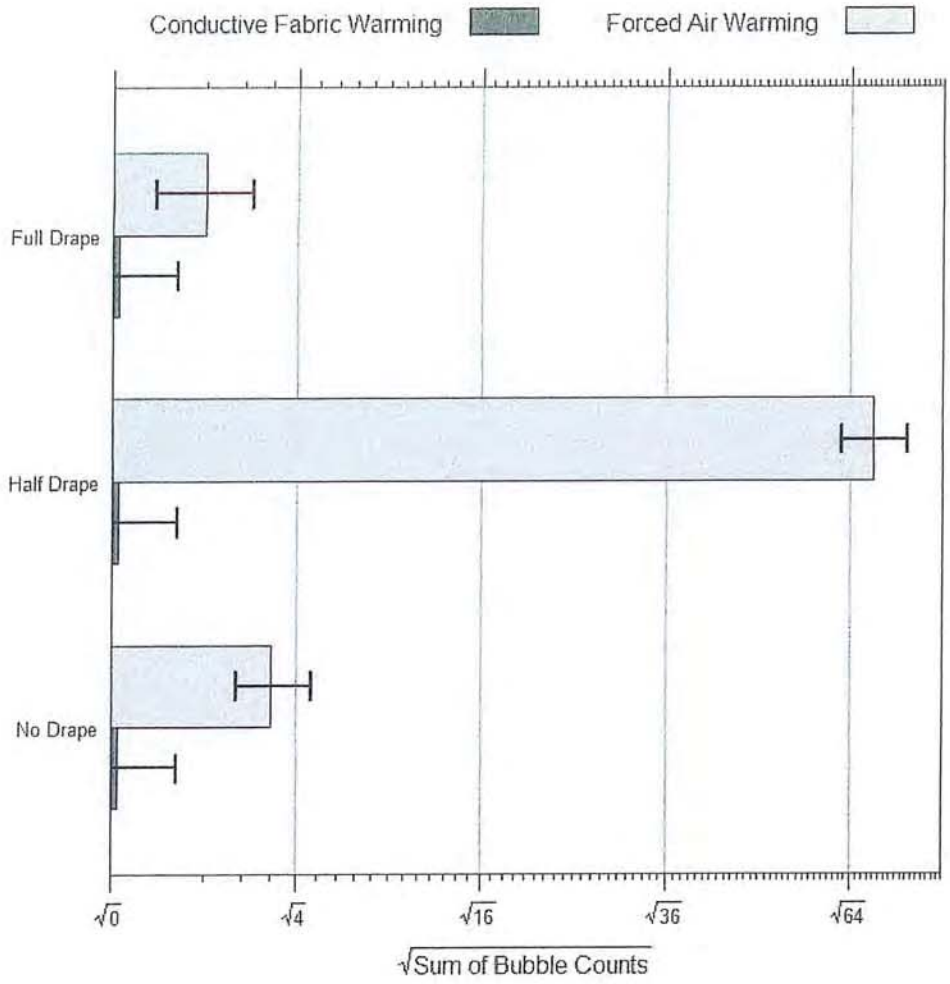

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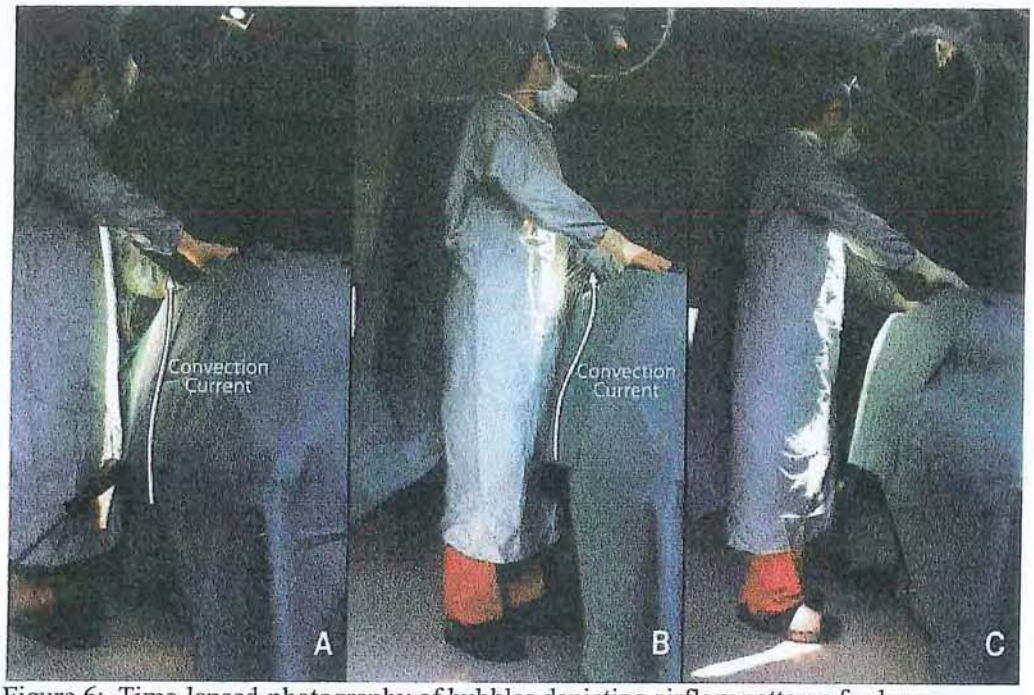

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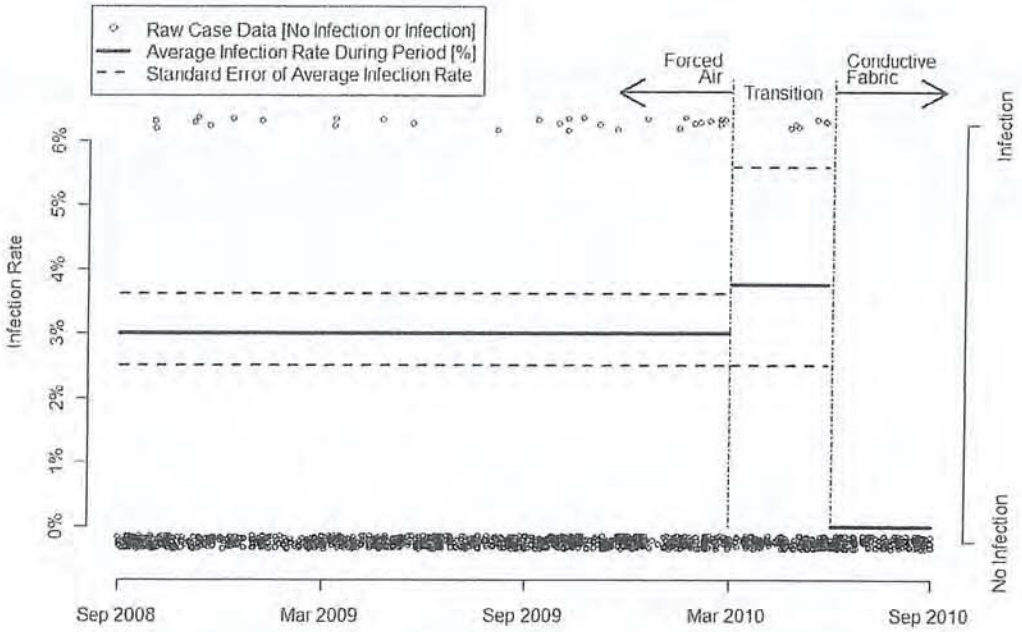

Figure 7: Infection data for n=1290 joint replacement cases with the outcome plotted on the right hand axis (data is jittered to avoid overprinting). Average infection rates for each period (Forced air, Transition, or Conductive Fabric) are plotted on the left hand axis. Standard error of the mean was estimated using logistic regression.

References

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Forced Air Warming and Ultra-Clean Ventilation Do Not Mix: The effect of excess vented heat on clean-airflow patterns.

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Key words: surgical site infection, forced air warming, laminar air flow, operating room environmental contamination, operating room ventilation

Abstract

Introduction: Ultra-clean ventilation is designed to protect the surgical site from airborne pathogens. However, ventilation performance is fragile and depends critically on airflow volumes and temperature gradients. Patient warming systems represent a disruption risk via the excess heat they release. Therefore, we compared the effects of two patient warming systems – (1) conductive fabric and (2) forced air – on clean-airflow patterns over the surgical site during orthopedic and spinal implant procedures.

Methods: A mannequin was draped for (1) a hip prosthesis and (2) a lower lumbar spinal implant in a partial-walled ultra-clean theater. Neutral buoyancy detergent bubbles were released under the anesthesia drape and at floor level to visualize air-currents and assess the mobilization of resident air into the clean-airflow over the surgical site. For the hip prosthesis, a randomized design assessed the effects upper-body warming system and anesthesia drape height on bubbles reaching the surgical site. For the spinal, the effect of lower-body warming system was assessed with time-lapsed-photography of bubbles. Lastly, joint sepsis rates were tracked for a 2 year period over which a change from forced air to conductive fabric was implemented.

Results: For the hip prosthesis, bubble counts were significantly higher for forced air than conductive fabric for laid-down (3 versus 0; $p=0.010$) and half-height (68 versus 0; $p<0.001$) anesthesia draping; differences for full-height draping were insignificant (1 versus 0; $p=0.283$). For the spinal, time-lapsed-photography showed forced air to establish upwards convection currents that transported floor air into the surgical site; this convection current was not present with conductive fabric. Joint sepsis infection rates were reduced after the implementation of conductive fabric warming (0% for n=161) versus prior rates with forced air (3.0% for n=936).

Conclusion: Excess heat from forced air warming disrupted clean-airflow patterns over the surgical site and generated upward convection currents, which transported non-sterile air from the floor and the anesthesia side of the drape into the surgical site; conductive fabric warming had no such effects. Observation of joint sepsis rates suggests an empirical reduction in infection with conductive fabric warming in orthopedics.

Number of words: 339

Introduction

Although most famously remembered for pioneering the hip arthroplasty, Sir John Charnley was among the first to recognize the critical role of operating theater (OT) ventilation in preventing joint sepsis. Charnley postulated that the "surgical implant might provide a nidus for the growth of airborne bacteria which ordinarily are accepted as non-pathogenic." Research efforts confirmed Charnley's insights through animal studies and a national clinical trial involving over 8000 operations that demonstrated the efficacy of clean air for the reduction of arthroplasty infection rates. As such, ultra-clean ventilation became the standard for orthopedic procedures. Ultra-clean ventilation protects the surgical site from airborne contamination through the constant delivery of a downward uniform velocity (0.3 to 0.5 m/s) highly filtered (>99.997%) airflow. However, the performance of ultra-clean ventilation depends critically on air-flow volumes and proper temperature gradients, the latter of which may be disrupted by excess heat released from patient warming devices.

The vented airflow from forced air warming is released at 43°C, which is often 20°C above ambient OT conditions. The release of such thermal energy has the potential to establish temperature gradients that impede the downward velocity of the OT ventilation airflows. Further, reductions in downward flow velocity have been shown to increase contaminant entrainment into the surgical site. Moreover, the release of excess heat may generate convection currents that rise against the downward airflows and mobilize non-sterile floor-level air into the surgical site.

Air-free alternatives, such as conductive fabric warming, have been developed that are comparably effective to forced air for the prevention of surgical hypothermia. These alternatives have much higher thermal efficiencies than forced air warming and, therefore, release only a fraction of the excess heat. As such, there is a need to critically assess the impact of forced air warming versus air-free alternatives on ultra-clean ventilation performance. Specifically, we compared the effects of (1) conductive fabric and (2) forced air warming on clean-airflow patterns over the surgical site in a partial-walled ultra-clean OT during two procedures representing the variety of implantable

operations typically encountered: 1) a hip arthroplasty with upper-body warming, and 2) a lower lumbar spinal with lower-body warming. Ventilation airflow patterns were visualized using neutrally buoyant detergent bubbles and observational data on joint sepsis rates were compared for the period each warming device was in clinical use.

Methods

Ultra-Clean Operating Theater Characteristics:

Experiments were carried out in a partial-walled ultra-clean OT (ExFlow 90, Howorth, United Kingdom) used for orthopedic and spinal surgery at Wansbeck Hospital (Ashington, United Kingdom). Validation and verification checks per HTM 2025 showed the OT airflows to be within specification and having a mean velocity of 0.44 m/s two-meters off the floor, which is above the threshold required by the standards (0.38 m/s). However, a slight airflow imbalance was detected during validation testing due to the location of the theater prep room that affected the results of a single particle entrainment test; entrainment values were 12% at that location, which marginally exceeded the recommended threshold of 10%. This slight discrepancy was unlikely to have any effect on the results of the study. Further, smoke testing detected normal airflow patterns under the canopy and the OT passed microbial contamination testing.

Airflow Visualization Procedures:

High intensity lighting was used to illuminate neutrally buoyant detergent bubbles having a 4 mm average diameter (referred to herein as "bubbles"). "Bubbles" were produced by a bubble generator (Sage Action, Ithaca, NY), which utilized a helium-mixed air supply, detergent, and centripetal bubble size classification filter. The bubble generator is specifically designed and validated for the visualization of air currents. For photography, a digital camera (D300, Nikon, Melville, NY) was employed and shutter exposure time was set to ¼ of a second for time-lapsed-photography.

Experimental Setup: Hip Arthroplasty

A mannequin was laid in the supine position on an operating table (Table Mfgr) and draped with a 3-piece orthopedic kit (Molnlycke Health Care) in accordance with standard protocols (**Fig 1**). A surgeon, dressed in occlusive clothing with head gear (MFGR), and an anesthesiologist stood motionless in front of the surgical site and behind the anesthesia screen. At the head of the operating table, the surgical drape was either: 1) clipped to the ceiling to create a barrier between the surgical site and anesthesia area (full-drape); 2) clipped to IV poles and raised 0.75 meters above the operating table (half-

drape); or 3) laid-down over the mannequin's head (laid-down). The experimental upper-body warming treatment was introduced under the drape and was either: 1) a torso forced air blanket (Bair Hugger Model 540, Arizant Healthcare, Eden Prairie, MN); or 2) a torso conductive fabric blanket (Hot Dog Model B110, Augustine Temperature Management, Eden Prairie, MN). The blankets were powered by standard controllers (conductive fabric - Model WC02, Augustine Temperature Management; forced air - Model 750, Arizant Healthcare). "Bubbles" were introduced at the neck of the mannequin to track under-drape resident air movements in the region where the excess patient warming heat was being released.

Experimental Setup: Lower lumbar spinal

The same mannequin was laid in the prone position on the operating table and four drapes were arranged in a "square" configuration (MFGR) with the anesthesia screen at full-height in accordance with standard protocols (**Fig 2**). A single surgeon stood motionless next to the surgical site for all experiments. The experimental lower-body warming treatment was introduced under the drape and was either: 1) a lower-body forced air blanket (Bair Hugger Model 525, Arizant Healthcare); or 2) a lower-body conductive fabric blanket (Hot Dog Model B103, Augustine Temperature Management). The blankets were powered by the same controllers as listed above. "Bubbles" were introduced at floor level between the surgeon's body and the operating room table in the region where the patient warming excess heat was being released.

Sampling Procedures

Hip Arthroplasty: Bubble counts over the surgical site were measured for each experimental treatment using a sequence of 5 photographs taken at 10 second intervals. The number of bubbles reaching the surgical site was determined by counting the number of bubbles in a 0.5 by 0.5 meter region over the surgical site in each photograph (**Fig 3**).
Lower Lumbar Spinal: Time-lapsed-photography was chosen over the use of bubble counts to show differences in ventilation performance between patient warming systems given the significant change in observed surgical site airflow patterns (see **Results**).

Experimental Design

Hip Arthroplasty: A replicated (n=2) $3^1 2^1$ full factorial design was employed to assess changes in bubble counts over the surgical site. The experimental factors considered were: 1) anesthesia screen: laid-down, half-screen, or full-screen; and 2) patient warming device: conductive fabric or forced air.

Lower Lumbar Spinal: No design was employed or necessary to demonstrate the difference in ventilation performance between forced air and conductive fabric patient warming systems (see **Results**).

Joint Sepsis Data

Joint sepsis data was collected for all orthopedic operations performed at the hospital during the 2-year period prior to the study, with dates comprising 9/1/2008 to 9/1/2010. A transition in patient warming systems from forced air to conductive fabric was made in all four orthopedic theaters starting 3/1/2010 and ending 6/1/2010.

Statistical Analysis

A Poisson regression model was fitted to the hip arthroplasty data having the sum of bubble counts for each experimental run (5 pictures) as the response and the two factors identified in the experimental design as predictors (including interaction). Reported values are predicted means (± standard error of the mean) for experimental factor combinations. Wald tests were used for significance.

A logistic regression model was fitted to the joint sepsis data having infection as the response and the period (forced air, transition, and conductive fabric warming) as predictors. Reported values are predicted mean infection rates (± standard error of the mean) for each period. Wald tests were used for significance.

Results

Hip Arthroplasty:

The number of bubbles reaching the surgical site measured the degree to which patient warming excess heat mobilized resident under-drape air over the anesthesia screen and into the surgical site. Bubble counts per photograph (**Fig 4**) suggest that forced air warming generated sufficient excess heat to mobilize resident under-drape air over the anesthesia screen. In contrast, conductive fabric warming did not generate sufficient excess heat to have the same mobilizing effect. Further, surgical drape position appeared to have a large effect on resident under-drape air mobilization into the surgical site for forced air warming, with the half-drape configuration resulting in the largest degree of resident-air mobilization.

Differences in the sum of bubble counts for each experimental run (**Fig 5**) were significant between conductive fabric and forced air warming for the drape configurations of half-drape (0 versus 68, $p<0.001$) and laid-down (0 versus 3, $p=0.010$); differences for full-drape (0 versus 1, $p=0.283$) were insignificant. It was necessary to model the sum of bubble counts for statistical inference; otherwise observations would not be independent.

Lower Lumbar Spinal:

Time-lapsed-photography showed forced air warming excess heat to generate hot-air convection currents that transported large quantities of floor-level resident air upwards and into the surgical site (**Fig 6**). These convection currents appeared to form in the space between the surgeon's body and the operating room table. In contrast, conductive fabric warming did not generate sufficient excess heat to establish such convection currents. Instead, with conductive fabric warming ventilation airflow patterns followed the intended path - downwards and away from the surgical site.

Joint Sepsis Rates:

A 2-year observation of orthopedic infections revealed a significant reduction in joint sepsis rates for the period conductive fabric warming was in clinical use versus forced air

warming, with average infection rates of 0.0% (n=165) versus 3.0% (n=965), respectively (**Fig 7**). An exact p-value cannot be calculated for this comparison given that there were no infections during the conductive fabric warming period. There was a 3 month transition period where both patient warming devices were used in the orthopedic theaters having an infection rate of 3.7% (n=160), which was not significantly different from the infection rate of 3.0% during the forced air warming period (p=0.62).

Discussion

This study compared the effects of two patient warming systems, forced air and conductive fabric, on ventilation performance in an ultra-clean operating theater during spinal and orthopedic procedures. Forced air warming excess heat was found to generate convection currents that disrupted clean-airflow patterns over the surgical site during both procedures. In contrast, conductive fabric warming released minimal excess heat and was shown to have no effect on ventilation performance in either procedure. The results also showed forced air warming excess heat to mobilize resident air from typically non-sterile areas (floor & under the anesthesia drape) into the surgical site, a finding that may have implications regarding surgical site sterility.

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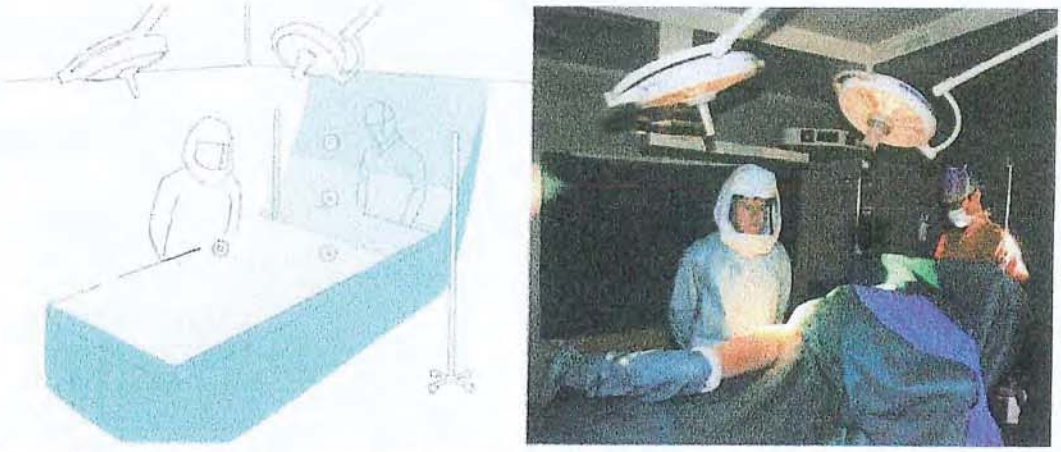

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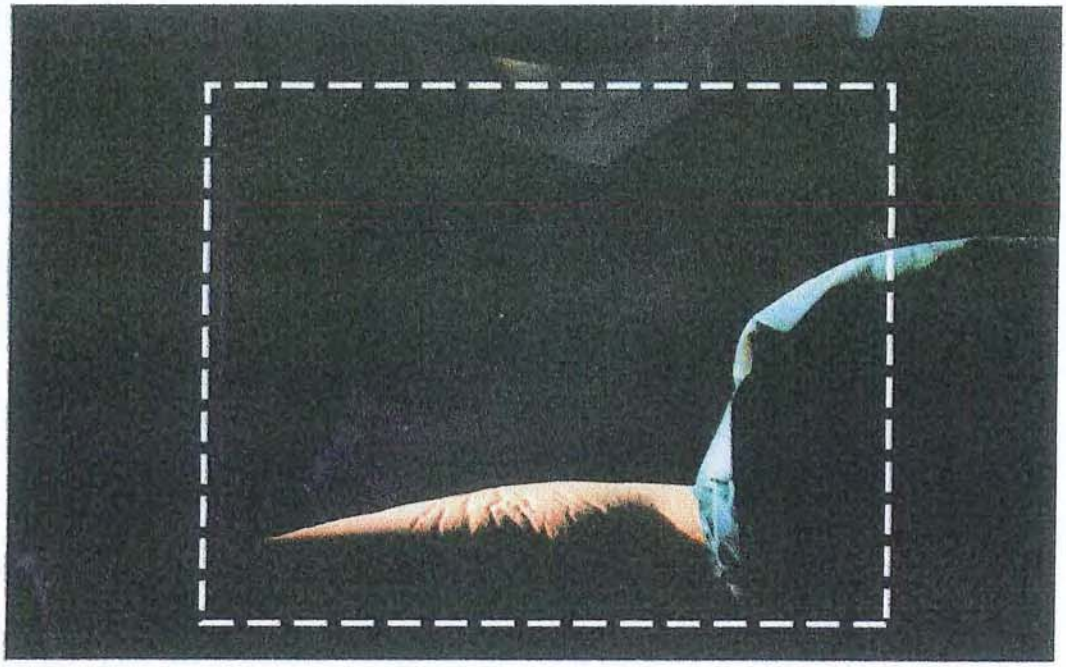

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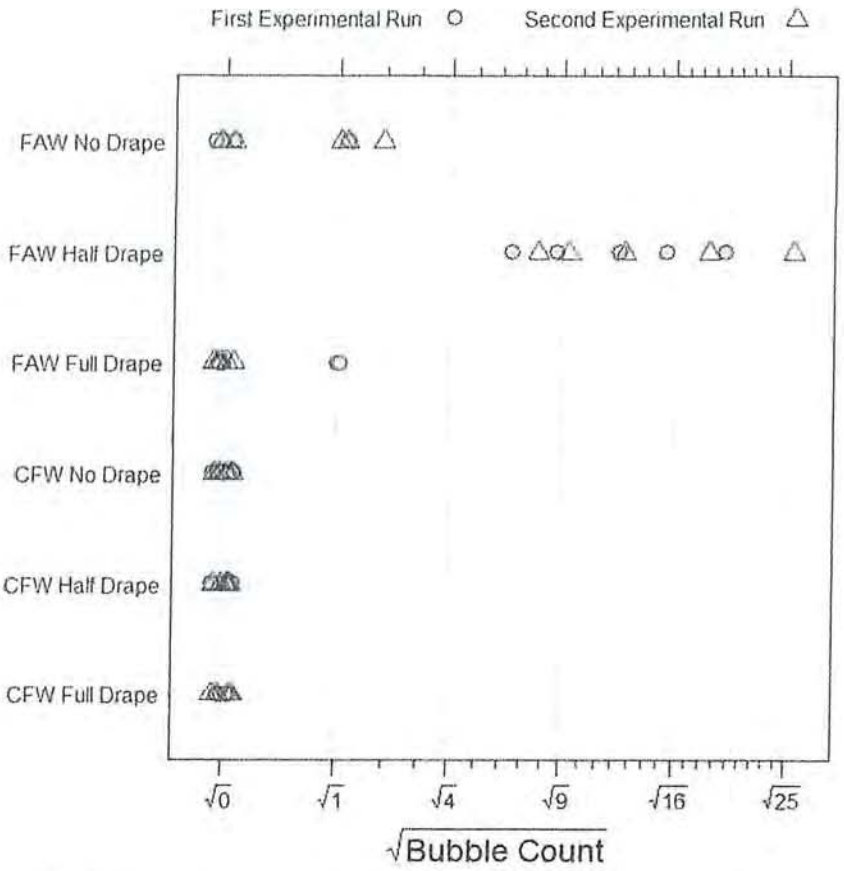

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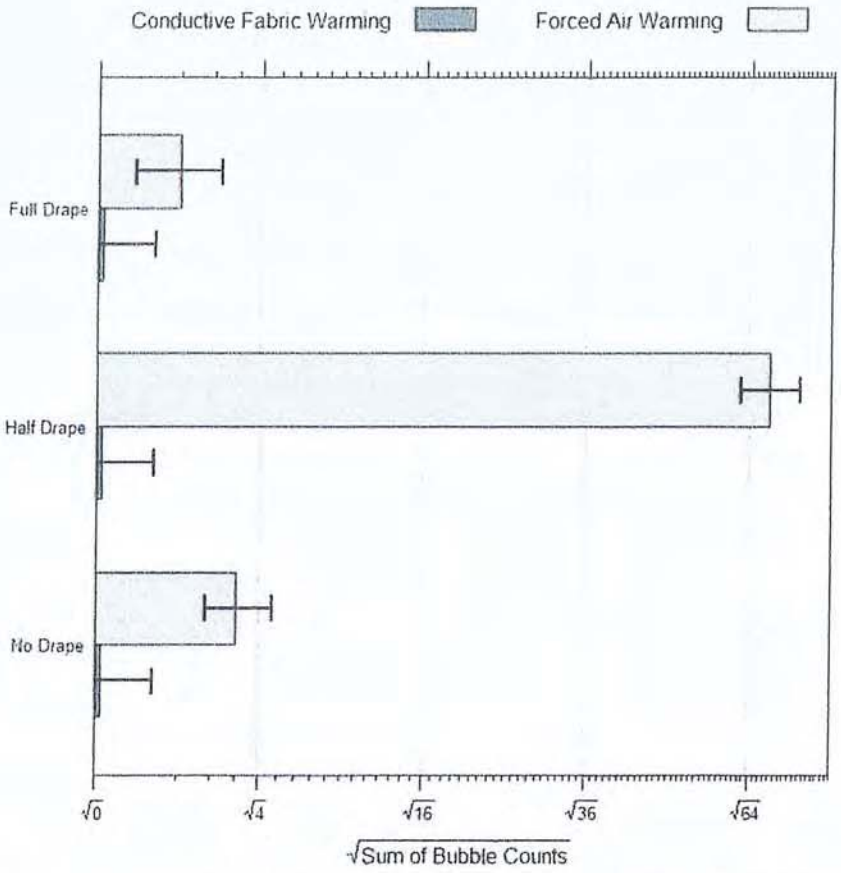

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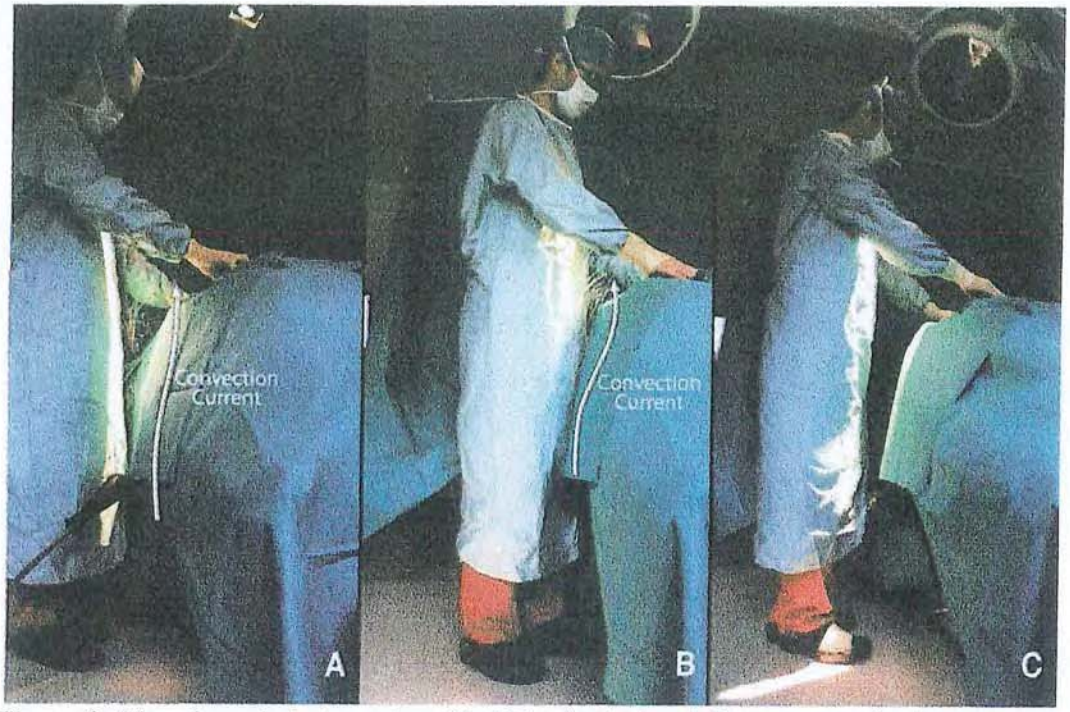

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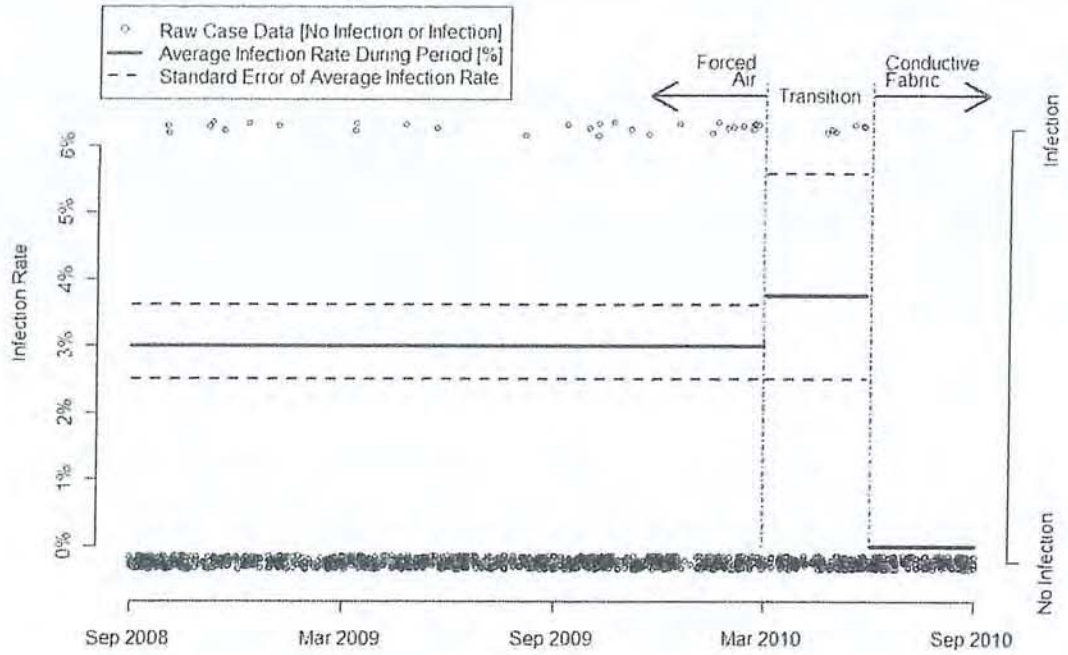

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Conflicts: Mike Reed reported no conflicts of interest

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Key words: surgical site infection, forced air warming, laminar air flow, operating room environmental contamination, operating room ventilation

Abstract

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Results: For the hip prosthesis, bubble counts were significantly higher for forced air than conductive fabric for laid-down (3 versus 0; $p=0.010$) and half-height (68 versus 0; $p<0.001$) anesthesia draping; differences for full-height draping were insignificant (1 versus 0; $p=0.283$). For the spinal, time-lapsed-photography showed forced air to establish upwards convection currents that transported floor air into the surgical site; this convection current was not present with conductive fabric. Joint sepsis infection rates were reduced after the implementation of conductive fabric warming (0% for n=161) versus prior rates with forced air (3.0% for n=936).

Conclusion: Excess heat from forced air warming disrupted clean-airflow patterns over the surgical site and generated upward convection currents, which transported non-sterile air from the floor and the anesthesia side of the drape into the surgical site; conductive fabric warming had no such effects. Observation of joint sepsis rates suggests an empirical reduction in infection with conductive fabric warming in orthopedics.

Number of words: 339

Introduction

Although most famously remembered for pioneering the hip arthroplasty, Sir John Charnley was among the first to recognize the critical role of operating theater (OT) ventilation in preventing joint sepsis. Charnley postulated that the "surgical implant might provide a nidus for the growth of airborne bacteria which ordinarily are accepted as non-pathogenic." Research efforts confirmed Charnley's insights through animal studies and a national clinical trial involving over 8000 operations that demonstrated the efficacy of clean air for the reduction of arthroplasty infection rates. As such, ultra-clean ventilation became the standard for orthopedic procedures. Ultra-clean ventilation protects the surgical site from airborne contamination through the constant delivery of a downward uniform velocity (0.3 to 0.5 m/s) highly filtered (>99.997%) airflow. However, the performance of ultra-clean ventilation depends critically on air-flow volumes and proper temperature gradients, the latter of which may be disrupted by excess heat released from patient warming devices.

The vented airflow from forced air warming is released at 43°C, which is often 20°C above ambient OT conditions. The release of such thermal energy has the potential to establish temperature gradients that impede the downward velocity of the OT ventilation airflows. Further, reductions in downward flow velocity have been shown to increase contaminant entrainment into the surgical site. Moreover, the release of excess heat may generate convection currents that rise against the downward airflows and mobilize non-sterile floor-level air into the surgical site.

Air-free alternatives, such as conductive fabric warming, have been developed that are comparably effective to forced air for the prevention of surgical hypothermia. These alternatives have much higher thermal efficiencies than forced air warming and, therefore, release only a fraction of the excess heat. As such, there is a need to critically assess the impact of forced air warming versus air-free alternatives on ultra-clean ventilation performance. Specifically, we compared the effects of (1) conductive fabric and (2) forced air warming on clean-airflow patterns over the surgical site in a partial-walled ultra-clean OT during two procedures representing the variety of implantable

operations typically encountered: 1) a hip arthroplasty with upper-body warming, and 2) a lower lumbar spinal with lower-body warming. Ventilation airflow patterns were visualized using neutrally buoyant detergent bubbles and observational data on joint sepsis rates were compared for the period each warming device was in clinical use.

Methods

Ultra-Clean Operating Theater Characteristics:

Experiments were carried out in a partial-walled ultra-clean OT (ExFlow 90, Howorth, United Kingdom) used for orthopedic and spinal surgery at Wansbeck Hospital (Ashington, United Kingdom). Validation and verification checks per HTM 2025 showed the OT airflows to be within specification and having a mean velocity of 0.44 m/s two-meters off the floor, which is above the threshold required by the standards (0.38 m/s). However, a slight airflow imbalance was detected during validation testing due to the location of the theater prep room that affected the results of a single particle entrainment test: entrainment values were 12% at that location, which marginally exceeded the recommended threshold of 10%. This slight discrepancy was unlikely to have any effect on the results of the study. Further, smoke testing detected normal airflow patterns under the canopy and the OT passed microbial contamination testing.

Airflow Visualization Procedures:

High intensity lighting was used to illuminate neutrally buoyant detergent bubbles having a 4 mm average diameter (referred to herein as "bubbles"). "Bubbles" were produced by a bubble generator (Sage Action, Ithaca, NY), which utilized a helium-mixed air supply, detergent, and centripetal bubble size classification filter. The bubble generator is specifically designed and validated for the visualization of air currents. For photography, a digital camera (500D, Canon, Surrey, UK) was employed and shutter exposure time was set to ¼ of a second for time-lapsed-photography.

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Experimental Setup: Hip Arthroplasty

A mannequin was laid in the supine position on an operating table (Table Mfgr) and draped with a 3-piece orthopedic kit (Molnlycke Health Care) in accordance with standard protocols (**Fig 1**). A surgeon, dressed in occlusive clothing with head gear (MFGR), and an anesthesiologist stood motionless in front of the surgical site and behind the anesthesia screen. At the head of the operating table, the surgical drape was either: 1) clipped to the ceiling to create a barrier between the surgical site and anesthesia area (full-drape); 2) clipped to IV poles and raised 0.75 meters above the operating table (half-

drape); or 3) laid-down over the mannequin's head (laid-down). The experimental upper-body warming treatment was introduced under the drape and was either: 1) a torso forced air blanket (Bair Hugger Model 540, Arizant Healthcare, Eden Prairie, MN); or 2) a torso conductive fabric blanket (Hot Dog Model B110, Augustine Temperature Management, Eden Prairie, MN). The blankets were powered by standard controllers (conductive fabric - Model WC02, Augustine Temperature Management; forced air - Model 750, Arizant Healthcare). "Bubbles" were introduced at the neck of the mannequin to track under-drape resident air movements in the region where the excess patient warming heat was being released.

Experimental Setup: Lower lumbar spinal

The same mannequin was laid in the prone position on the operating table and four drapes were arranged in a "square" configuration (MFGR) with the anesthesia screen at full-height in accordance with standard protocols (**Fig 2**). A single surgeon stood motionless next to the surgical site for all experiments. The experimental lower-body warming treatment was introduced under the drape and was either: 1) a lower-body forced air blanket (Bair Hugger Model 525, Arizant Healthcare); or 2) a lower-body conductive fabric blanket (Hot Dog Model B103, Augustine Temperature Management). The blankets were powered by the same controllers as listed above. "Bubbles" were introduced at floor level between the surgeon's body and the operating room table in the region where the patient warming excess heat was being released.

Sampling Procedures

Hip Arthroplasty: Bubble counts over the surgical site were measured for each experimental treatment using a sequence of 5 photographs taken at 10 second intervals. The number of bubbles reaching the surgical site was determined by counting the number of bubbles in a 0.5 by 0.5 meter region over the surgical site in each photograph (**Fig 3**).
Lower Lumbar Spinal: Time-lapsed-photography was chosen over the use of bubble counts to show differences in ventilation performance between patient warming systems given the significant change in observed surgical site airflow patterns (see **Results**).

Experimental Design

Hip Arthroplasty: A replicated (n=2) $3^1 2^1$ full factorial design was employed to assess changes in bubble counts over the surgical site. The experimental factors considered were: 1) anesthesia screen: laid-down, half-screen, or full-screen; and 2) patient warming device: conductive fabric or forced air.

Lower Lumbar Spinal: No design was employed or necessary to demonstrate the difference in ventilation performance between forced air and conductive fabric patient warming systems (see **Results**).

Joint Sepsis Data

Joint sepsis data was collected for all orthopedic operations performed at the hospital during the 2-year period prior to the study, with dates comprising 9/1/2008 to 9/1/2010. A transition in patient warming systems from forced air to conductive fabric was made in all four orthopedic theaters starting 3/1/2010 and ending 6/1/2010.

Statistical Analysis

A Poisson regression model was fitted to the hip arthroplasty data having the sum of bubble counts for each experimental run (5 pictures) as the response and the two factors identified in the experimental design as predictors (including interaction). Reported values are predicted means (± standard error of the mean) for experimental factor combinations. Wald tests were used for significance.

A logistic regression model was fitted to the joint sepsis data having infection as the response and the period (forced air, transition, and conductive fabric warming) as predictors. Reported values are predicted mean infection rates (± standard error of the mean) for each period. Wald tests were used for significance.

Results

Hip Arthroplasty:

The number of bubbles reaching the surgical site measured the degree to which patient warming excess heat mobilized resident under-drape air over the anesthesia screen and into the surgical site. Bubble counts per photograph (**Fig 4**) suggest that forced air warming generated sufficient excess heat to mobilize resident under-drape air over the anesthesia screen. In contrast, conductive fabric warming did not generate sufficient excess heat to have the same mobilizing effect. Further, surgical drape position appeared to have a large effect on resident under-drape air mobilization into the surgical site for forced air warming, with the half-drape configuration resulting in the largest degree of resident-air mobilization.

Differences in the sum of bubble counts for each experimental run (**Fig 5**) were significant between conductive fabric and forced air warming for the drape configurations of half-drape (0 versus 68, $p<0.001$) and laid-down (0 versus 3, $p=0.010$); differences for full-drape (0 versus 1, $p=0.283$) were insignificant. It was necessary to model the sum of bubble counts for statistical inference; otherwise observations would not be independent.

Lower Lumbar Spinal:

Time-lapsed-photography showed forced air warming excess heat to generate hot-air convection currents that transported large quantities of floor-level resident air upwards and into the surgical site (**Fig 6**). These convection currents appeared to form in the space between the surgeon's body and the operating room table. In contrast, conductive fabric warming did not generate sufficient excess heat to establish such convection currents. Instead, with conductive fabric warming ventilation airflow patterns followed the intended path - downwards and away from the surgical site.

Joint Sepsis Rates:

A 2-year observation of orthopedic infections revealed a significant reduction in joint sepsis rates for the period conductive fabric warming was in clinical use versus forced air

warming, with average infection rates of 0.0% (n=165) versus 3.0% (n=965), respectively (**Fig 7**). An exact p-value cannot be calculated for this comparison given that there were no infections during the conductive fabric warming period. There was a 3 month transition period where both patient warming devices were used in the orthopedic theaters having an infection rate of 3.7% (n=160), which was not significantly different from the infection rate of 3.0% during the forced air warming period (p=0.62).

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Discussion

This study compared the effects of two patient warming systems, forced air and conductive fabric, on ventilation performance in an ultra-clean operating theater during spinal and orthopedic procedures. Forced air warming excess heat was found to generate convection currents that disrupted clean-airflow patterns over the surgical site during both procedures. In contrast, conductive fabric warming released minimal excess heat and was shown to have no effect on ventilation performance in either procedure. The results also showed forced air warming excess heat to mobilize resident air from typically non-sterile areas (floor & under the anesthesia drape) into the surgical site, a finding that may have implications regarding surgical site sterility.

Perhaps the most striking finding was the detection of hot-air convection currents originating from where the "mass-flow" of hot air exhausted the forced air warming blanket: for the hip arthroplasty with upper-body warming, convection currents formed near the mannequin's head; for the spinal implant with lower-body warming, convection currents formed along the lower drape edge by the surgeon's legs. The formation of such convection currents may, at first, appear to be theoretically unsupported since forced air warming exhausts a heated airflow of only 40 cubic feet per minute into a ventilation environment having an airflow of 6000 cubic feet per minute. However, one must also consider the effects of surgical lighting, drapes, and personnel on ventilation performance, all of which create localized airflow disturbances that aid in convection current formation.

Prior research in ultra-clean ventilation theaters has shown surgical lighting to be a significant source of ventilation disruption through the downstream wake and associated recirculation zone. In our study, the use of "bubbles" allowed us to visualize this recirculation zone, which was found to extend about 1 meter below the body of each surgical light. "Bubbles" and, thus, resident air reaching this zone tended to remain suspended in this vortex for some time. The presence of a raised anesthesia drape was shown to further magnify the size and effect of this vortex, for the drape blocked the natural passage of air out of the ventilation field and created a "still zone" adjacent to the vortex. Lastly, the presence of a surgeon or anesthesiologist near this "still zone" created an additional ventilation flow blockage resulting in a situation where even the slightest movements, ones that would not normally cause ventilation disruption, adversely impacted the natural airflow patterns over the surgical site.

Under these fragile conditions, the "mass-flow" of hot forced air warming exhaust was sufficiently buoyant to push upwards within these locally compromised ventilation regions. For the hip arthroplasty, the compromised region was along the backside of the anesthesia drape. For the lower lumbar spinal implant, the compromised region was the channel between the surgeon's body and operating table. Both compromised regions resulted from a combination of lights, drapes, and personnel forming a pocket having the following characteristics: the pocket 1) was sheltered from the downward ventilation airflows; 2) extended into the region where the "mass-flow" of forced air warming exhaust was being vented; and, 3) formed a path that terminated near the surgical site. Due to the reduced ventilation velocity within the pocket, hot-air convection currents were able to form and resulted in the transport of floor-level and under-drape air into the surgical site.

The clinical concern regarding the formation of such convection currents is two-fold. First, these currents oppose the natural clean-airflow patterns that are intended to sweep contaminants down and away from the surgical site. Thus, contaminants released in the vicinity of the surgical site are less likely to be cleared. Second, the upward mobilization of floor-level and under-drape air could potentially compromise the sterility of the

surgical site, since resident air from these locations is typically laden with pathogens shed from the surgical staff. Further, even small elevations in contaminant exposure could be of clinical significance given that airborne derived infection risks are exponentially magnified with implantable procedures. Empirical support for the concept that observed convection currents resulted in increased surgical site contaminant exposure can be found in the observed reduction in hospital arthroplasty infection rates when a switch from forced air to conductive fabric warming was implemented. However, this infection data is observational in nature and does not prove that such a relationship exists since we were unable to control for other infection reduction measures instituted by the hospital over the 2-year period.

Further, the present study is somewhat limited in that we assessed the movements of "bubbles" as a surrogate for the movement of pathogenic contaminants. Thus, the clinical relevance of our findings depend on two assumptions: 1) that floor-level and under-drape air is non-sterile; and 2) that airborne contaminant concentrations from these locations represent a significant infection risk relative to other contamination sources. Moreover, the entire field of prior research assessing forced air warming excess heat and changes in airborne pathogen levels during implantable procedures is limited to a single orthopedic study, in which forced air warming resulted in elevated microbial counts over the surgical site. However, the contamination increase was deemed to be far less than that resulting from personnel movements and such increases did not exceed recommended bacterial levels. Yet, it is unknown how these results translate over the range of implantable procedures. Even minor differences in factors such as surgical draping, procedural practices, and theater dress are likely to have large effects on both floor-level and under-drape contaminant levels and the dynamics of convection current formation.

Until the effects of forced air warming excess heat on ventilation disruption can be fully evaluated in regards to affecting the sterility of the surgical site, the use of air-free patient warming alternatives might be recommended for implant procedures carried out in ultra-clean theaters.

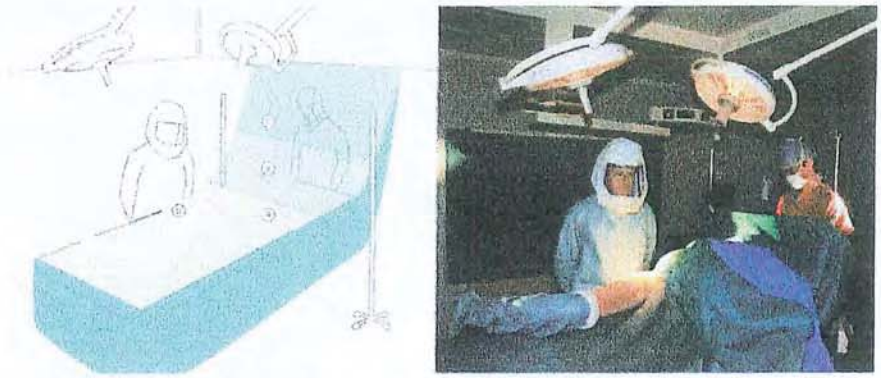

Figure 1: Hip arthroplasty setup with upper-body warming, showing: surgical drape positions of laid-down (A), half-drape (B), and full-drape (C) and surgical site location (D)

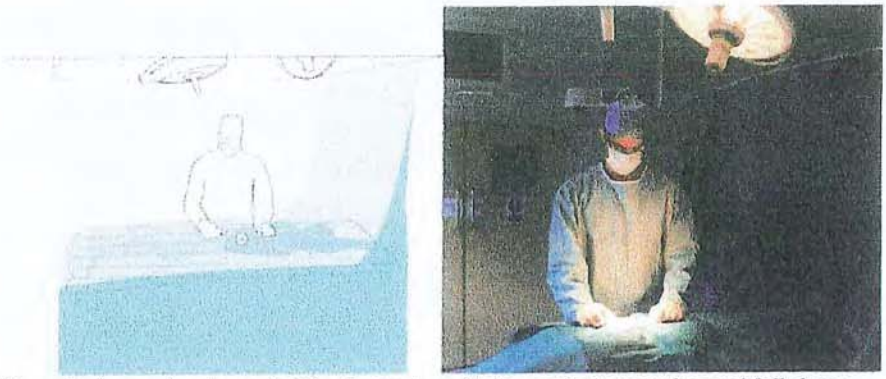

Figure 2: Lower lumbar spinal implant setup with lower-body warming and full-drape, showing: surgical site location (A).

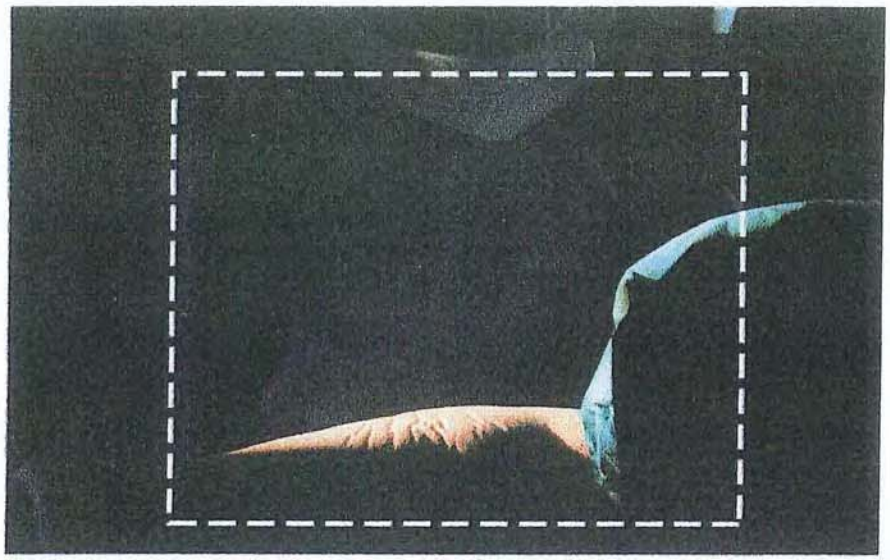

Figure 3: Definition of region where bubble counts were performed over the surgical site for hip arthroplasty with upper-body warming. A picture shows bubbles (white steaks) appearing in the photograph for the experimental setup of forced air warming and half-drape.

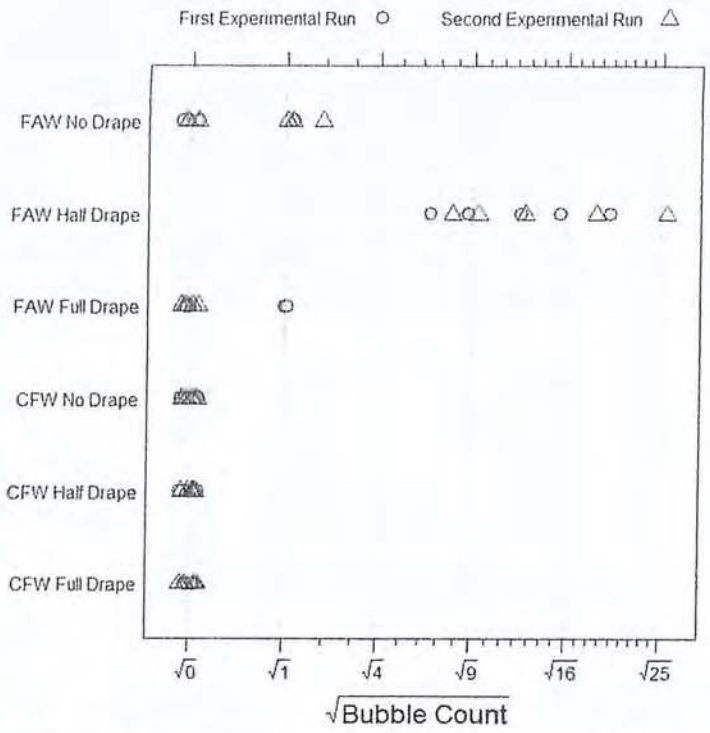

Figure 4: Bubble counts over the surgical site for each photograph (data is jittered to avoid overprinting). 5 photographs were taken for each experimental run.
Abbreviations: FAW, Forced Air Warming; CFW, Conductive Fabric Warming.

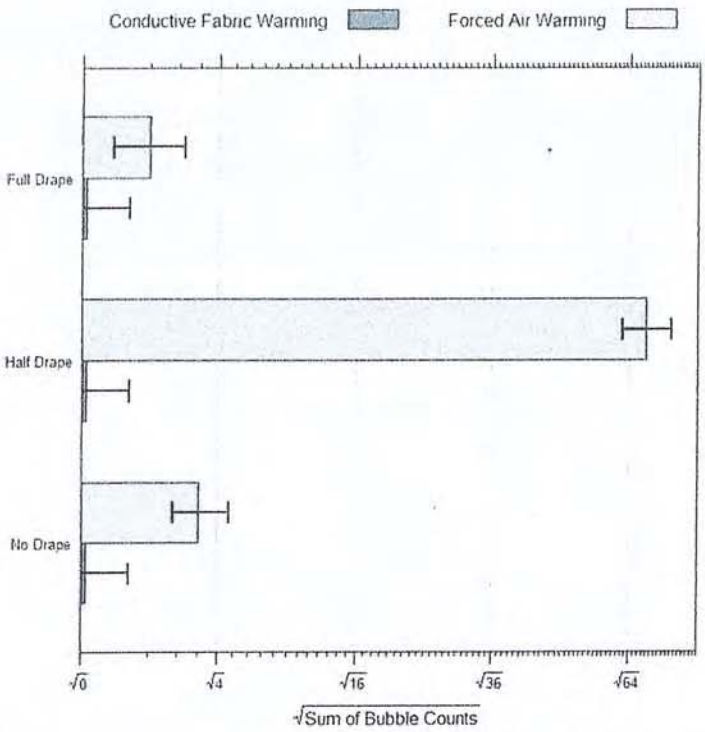

Figure 5: Average bubble count for experimental runs when the bubble counts are summed over the 5 photographs (±Standard Error of the Mean).

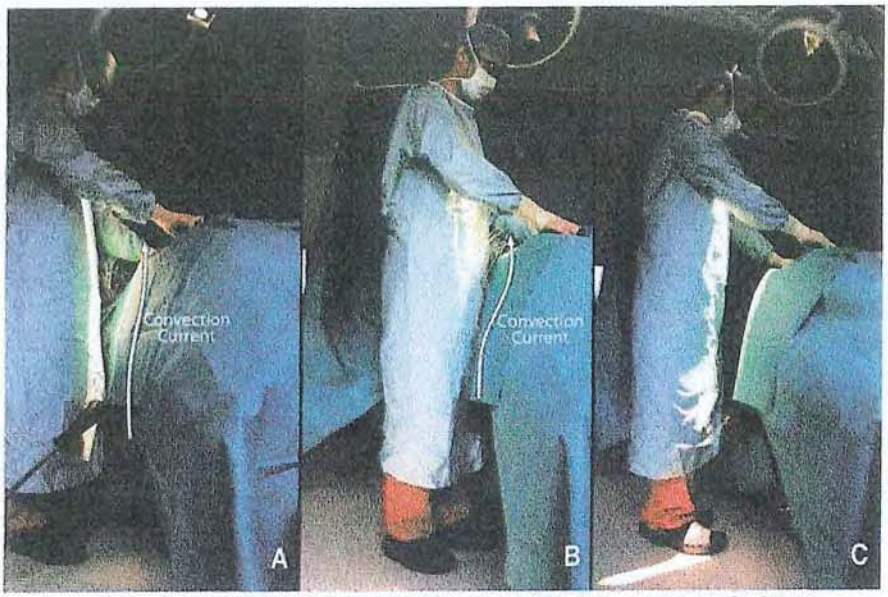

Figure 6: Time-lapsed-photography of bubbles depicting airflow patterns for lower lumbar spinal implant procedure with: (A & B) Forced air warming with resulting convection currents annotated and (C) conductive fabric warming.

In ☺ I'm standing further away from the table. I'm sure we saw the effect when I wasn't as far away, it could be argued that the effect is different because of surgeon proximity to table? Small point I know

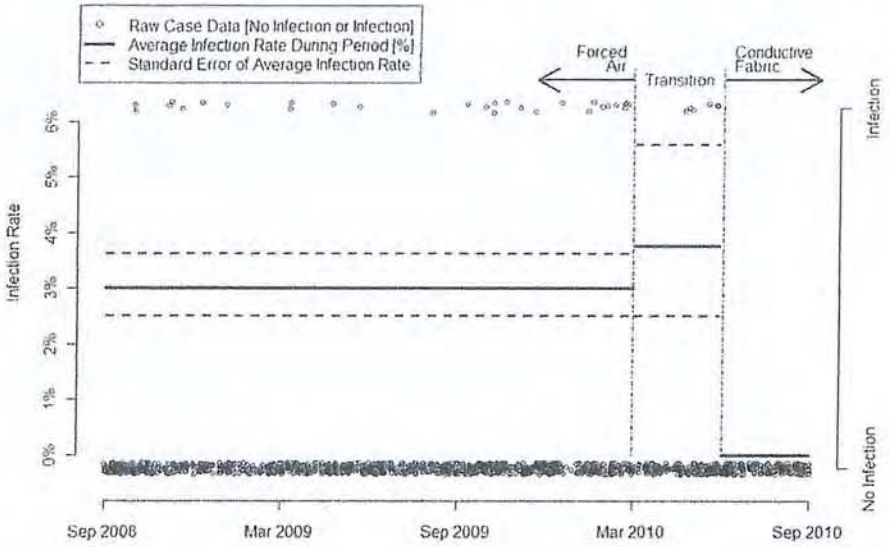

Figure 7: Infection data for n=1290 joint replacement cases with the outcome plotted on the right hand axis (data is jittered to avoid overprinting). Average infection rates for each period (Forced air, Transition, or Conductive Fabric) are plotted on the left hand axis. Standard error of the mean was estimated using logistic regression.

References

Document Name: Manuscript_Reed_5.docx

Forced Air Warming and Ultra-Clean Ventilation Do Not Mix: The effect of excess vented heat on clean-airflow patterns.

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the operating table (half-drape); or 3) laid-down over the mannequin's head (laid-down). The experimental upper-body warming treatment was introduced under the drape and was either: 1) a torso forced air blanket (Bair Hugger Model 540, Arizant Healthcare, Eden Prairie, MN); or 2) a torso conductive fabric blanket (Hot Dog Model B110, Augustine Temperature Management, Eden Prairie, MN). The blankets were powered by standard controllers (conductive fabric - Model WC02, Augustine Temperature Management; forced air - Model 750, Arizant Healthcare). "Bubbles" were introduced at the neck of the mannequin to track under-drape resident air movements in the region where the excess patient warming heat was being released.

Experimental Setup: Lower lumbar spinal

The same mannequin was laid in the prone position on the operating table and four drapes were arranged in a "square" configuration (Molnlycke Health Care) with the anesthesia screen at full-height in accordance with standard protocols (**Fig 2**). A single surgeon stood motionless next to the surgical site for all experiments. The experimental lower-body warming treatment was introduced under the drape and was either: 1) a lower-body forced air blanket (Bair Hugger Model 525, Arizant Healthcare); or 2) a lower-body conductive fabric blanket (Hot Dog Model B103, Augustine Temperature Management). The blankets were powered by the same controllers as listed above. "Bubbles" were introduced at floor level between the surgeon's body and the operating room table in the region where the patient warming excess heat was being released.

Sampling Procedures

Hip Arthroplasty: Bubble counts over the surgical site were measured for each experimental treatment using a sequence of 5 photographs taken at 10 second intervals. The number of bubbles reaching the surgical site was determined by counting the number of bubbles in a 0.5 by 0.5 meter region over the surgical site in each photograph (**Fig 3**).
Lower Lumbar Spinal: Time-lapsed-photography was chosen over the use of bubble counts to show differences in ventilation performance between patient warming systems given the significant change in observed surgical site airflow patterns (see **Results**).

Experimental Design

Hip Arthroplasty: A replicated (n=2) $3^1 2^1$ full factorial design was employed to assess changes in bubble counts over the surgical site. The experimental factors considered were: 1) anesthesia screen: laid-down, half-screen, or full-screen; and 2) patient warming device: conductive fabric or forced air.

Lower Lumbar Spinal: No design was employed or necessary to demonstrate the difference in ventilation performance between forced air and conductive fabric patient warming systems (see **Results**).

Joint Sepsis Data

Joint sepsis data was collected for all orthopedic operations performed at the hospital during the 2-year period prior to the study, with dates comprising 9/1/2008 to 9/1/2010. A transition in patient warming systems from forced air to conductive fabric was made in all four orthopedic theaters starting 3/1/2010 and ending 6/1/2010.

Statistical Analysis

A Poisson regression model was fitted to the hip arthroplasty data having the sum of bubble counts for each experimental run (5 pictures) as the response and the two factors identified in the experimental design as predictors (including interaction). Reported values are predicted means (± standard error of the mean) for experimental factor combinations. Wald tests were used for significance.

A logistic regression model was fitted to the joint sepsis data having infection as the response and the period (forced air, transition, and conductive fabric warming) as predictors. Reported values are predicted mean infection rates (± standard error of the mean) for each period. Wald tests were used for significance.

Results

Hip Arthroplasty:

The number of bubbles reaching the surgical site measured the degree to which patient warming excess heat mobilized resident under-drape air over the anesthesia screen and into the surgical site. Bubble counts per photograph (**Fig 4**) suggest that forced air warming generated sufficient excess heat to mobilize resident under-drape air over the anesthesia screen. In contrast, conductive fabric warming did not generate sufficient excess heat to have the same mobilizing effect. Further, surgical drape position appeared to have a large effect on resident under-drape air mobilization into the surgical site for forced air warming, with the half-drape configuration resulting in the largest degree of resident-air mobilization.

Differences in the sum of bubble counts for each experimental run (**Fig 5**) were significant between conductive fabric and forced air warming for the drape configurations of half-drape (0 versus 68, $p<0.001$) and laid-down (0 versus 3, $p=0.010$); differences for full-drape (0 versus 1, $p=0.283$) were insignificant. It was necessary to model the sum of bubble counts for statistical inference; otherwise observations would not be independent.

Lower Lumbar Spinal:

Time-lapsed-photography showed forced air warming excess heat to generate hot-air convection currents that transported large quantities of floor-level resident air upwards and into the surgical site (**Fig 6**). These convection currents appeared to form in the space between the surgeon's body and the operating room table. In contrast, conductive fabric warming did not generate sufficient excess heat to establish such convection currents. Instead, with conductive fabric warming ventilation airflow patterns followed the intended path - downwards and away from the surgical site.

Joint Sepsis Rates:

A 2-year observation of orthopedic infections revealed a significant reduction ($p=0.007$) in joint sepsis rates for the period conductive fabric warming was in clinical use versus

forced air warming, with average infection rates of 0.0% (n=165) versus 3.0% (n=965), respectively (**Fig 7**). The reported p-value is the probability of observing 0 infections in 165 cases given a 3.0% infection rate and a binomial distribution, since model asymptotics are unstable in the region where p≈0. There was a 3 month transition period where both patient warming devices were used in the orthopedic theaters having an infection rate of 3.7% (n=160), which was not significantly different from the infection rate of 3.0% during the forced air warming period (p=0.62).

Discussion

This study compared the effects of two patient warming systems, forced air and conductive fabric, on ventilation performance in an ultra-clean operating theater during spinal and orthopedic procedures. Forced air warming excess heat was found to generate convection currents that disrupted clean-airflow patterns over the surgical site during both procedures. In contrast, conductive fabric warming released minimal excess heat and was shown to have no effect on ventilation performance in either procedure. The results also showed forced air warming excess heat to mobilize resident air from typically non-sterile areas (floor & under the anesthesia drape) into the surgical site, a finding that may have implications regarding surgical site sterility.

Perhaps the most striking finding was the detection of hot-air convection currents originating from where the "mass-flow" of hot air exhausted the forced air warming blanket: for the hip arthroplasty with upper-body warming, convection currents formed near the mannequin's head; for the spinal implant with lower-body warming, convection currents formed along the lower drape edge by the surgeon's legs. The formation of such convection currents may, at first, appear to be theoretically unsupported since forced air warming exhausts a heated airflow of only 40 cubic feet per minute into a ventilation environment having an airflow of 6000 cubic feet per minute.[16] However, one must also consider the effects of surgical lighting, drapes, and personnel on ventilation performance, all of which create localized airflow disturbances that aid in convection current formation.

Prior research in ultra-clean ventilation theaters has shown surgical lighting to be a significant source of ventilation disruption through the downstream wake and associated recirculation zone.[15] In our study, the use of "bubbles" allowed us to visualize this recirculation zone, which was found to extend about 1 meter below the body of each surgical light. "Bubbles" and, thus, resident air reaching this zone tended to remain suspended in this vortex for some time. The presence of a raised anesthesia drape was shown to further magnify the size and effect of this vortex, for the drape blocked the natural passage of air out of the ventilation field and created a "still zone" adjacent to the vortex. Lastly, the presence of a surgeon or anesthesiologist near this "still zone" created an additional ventilation flow blockage[17] resulting in a situation where even the slightest movements, ones that would not normally cause ventilation disruption, adversely impacted the natural airflow patterns over the surgical site.

Under these fragile conditions, the "mass-flow" of hot forced air warming exhaust was sufficiently buoyant to push upwards within these locally compromised ventilation regions. For the hip arthroplasty, the compromised region was along the backside of the anesthesia drape. For the lower lumbar spinal implant, the compromised region was the channel between the surgeon's body and operating table. Both compromised regions resulted from a combination of lights, drapes, and personnel forming a pocket having the following characteristics: the pocket 1) was sheltered from the downward ventilation airflows; 2) extended into the region where the "mass-flow" of forced air warming exhaust was being vented; and, 3) formed a path that terminated near the surgical site. Due to the reduced ventilation velocity within the pocket, hot-air convection currents were able to form and resulted in the transport of floor-level and under-drape air into the surgical site.

The clinical concern regarding the formation of such convection currents is two-fold. First, these currents oppose the natural clean-airflow patterns that are intended to sweep contaminants down and away from the surgical site.[18] Thus, contaminants released in the vicinity of the surgical site are less likely to be cleared. Second, the upward mobilization of floor-level and under-drape air could potentially compromise the sterility of the

surgical site, since resident air from these locations is typically laden with pathogens shed from the surgical staff.[19] Further, even small elevations in contaminant exposure could be of clinical significance given that airborne derived infection risks are exponentially magnified with implantable procedures.[20] Empirical support for the concept that observed convection currents resulted in increased surgical site contaminant exposure can be found in the observed reduction in hospital arthroplasty infection rates when a switch from forced air to conductive fabric warming was implemented. However, this infection data is observational in nature and does not prove that such a relationship exists since we were unable to control for other infection reduction measures instituted by the hospital over the 2-year period.

Further, the present study is somewhat limited in that we assessed the movements of "bubbles" as a surrogate for the movement of pathogenic contaminants. Thus, the clinical relevance of our findings depend on two assumptions: 1) that floor-level and under-drape air is non-sterile; and 2) that airborne contaminant concentrations from these locations represent a significant infection risk relative to other contamination sources. Moreover, the entire field of prior research assessing forced air warming excess heat and changes in airborne pathogen levels during implantable procedures is limited to a single orthopedic study, in which forced air warming resulted in elevated microbial counts over the surgical site.[21] However, the contamination increase was deemed to be far less than that resulting from personnel movements and such increases did not exceed recommended bacterial levels. Yet, it is unknown how these results translate over the range of implantable procedures. Even minor differences in factors such as surgical draping, procedural practices, and theater dress are likely to have large effects on both floor-level and under-drape contaminant levels and the dynamics of convection current formation.

Until the effects of forced air warming excess heat on ventilation disruption can be fully evaluated in regards to affecting the sterility of the surgical site, the use of air-free patient warming alternatives might be recommended for implant procedures carried out in ultra-clean theaters.

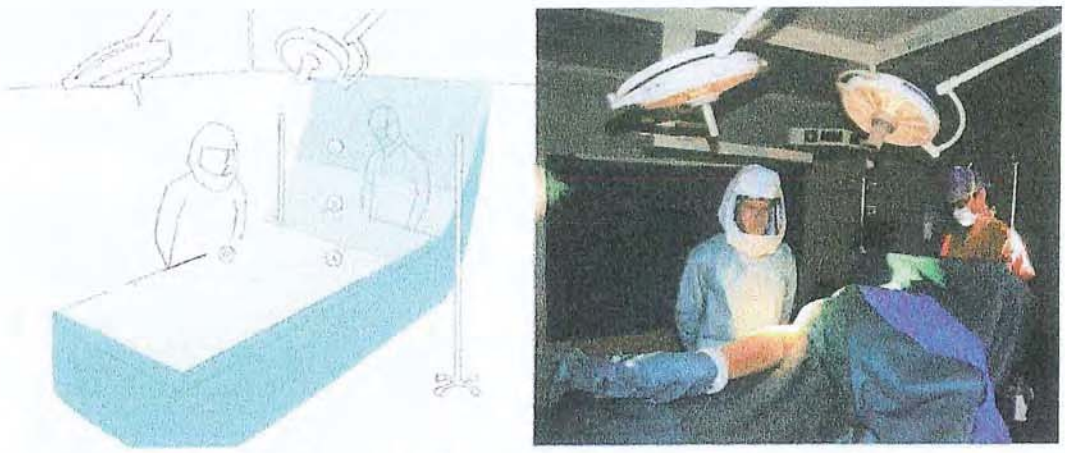

Figure 1: Hip arthroplasty setup with upper-body warming, showing: surgical drape positions of laid-down (A), half-drape (B), and full-drape (C) and surgical site location (D)

Figure 2: Lower lumbar spinal implant setup with lower-body warming and full-drape, showing: surgical site location (A).

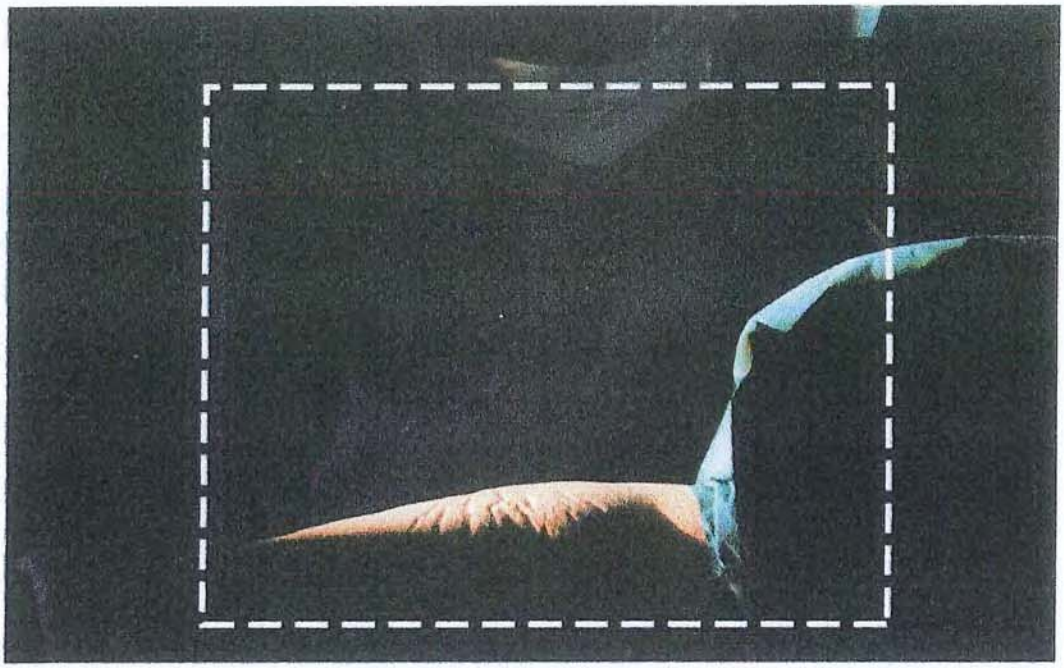

Figure 3: Definition of region where bubble counts were performed over the surgical site for hip arthroplasty with upper-body warming. A picture shows bubbles (white steaks) appearing in the photograph for the experimental setup of forced air warming and half-drape.

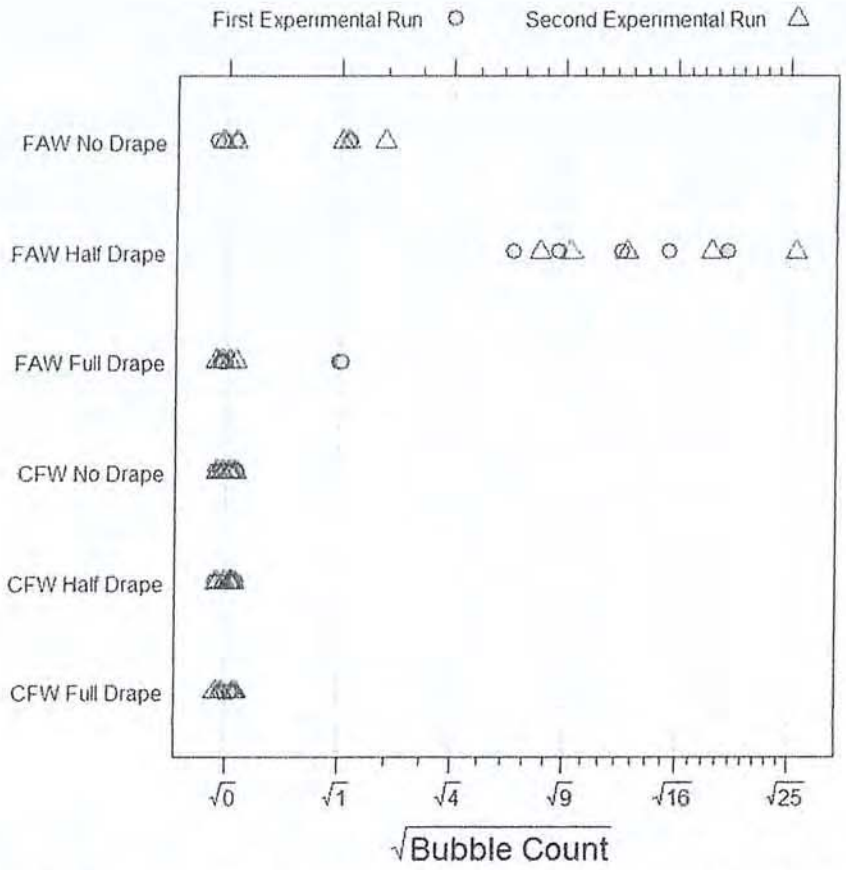

Figure 4: Bubble counts over the surgical site for each photograph (data is jittered to avoid overprinting). 5 photographs were taken for each experimental run.
Abbreviations: FAW, Forced Air Warming; CFW, Conductive Fabric Warming.

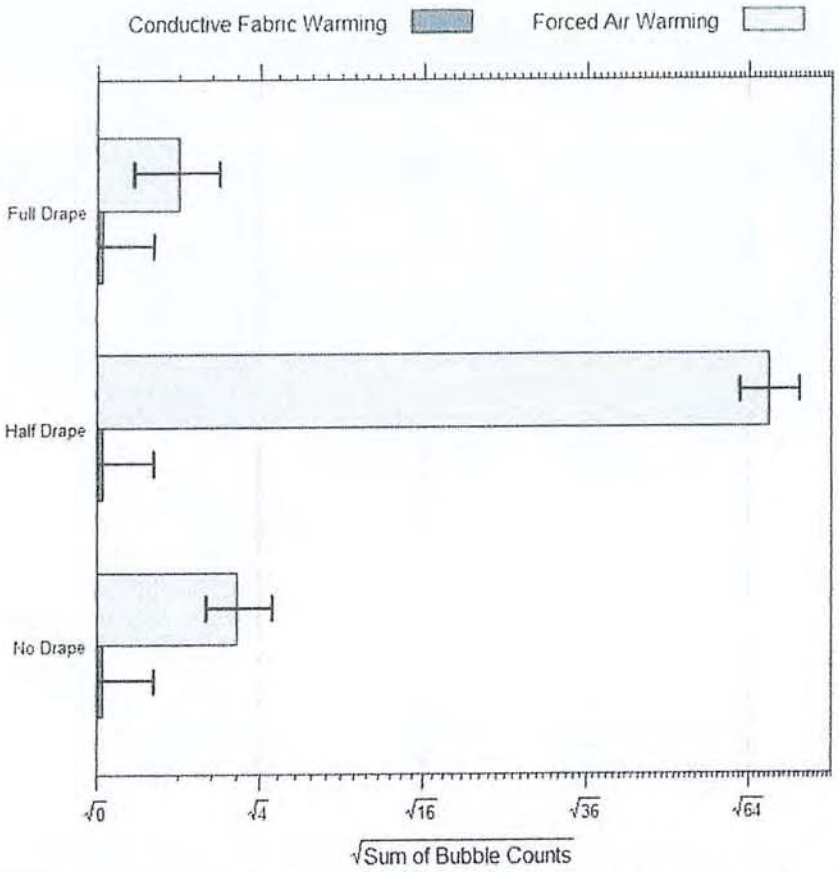

Figure 5: Average bubble count for experimental runs when the bubble counts are summed over the 5 photographs (±Standard Error of the Mean).

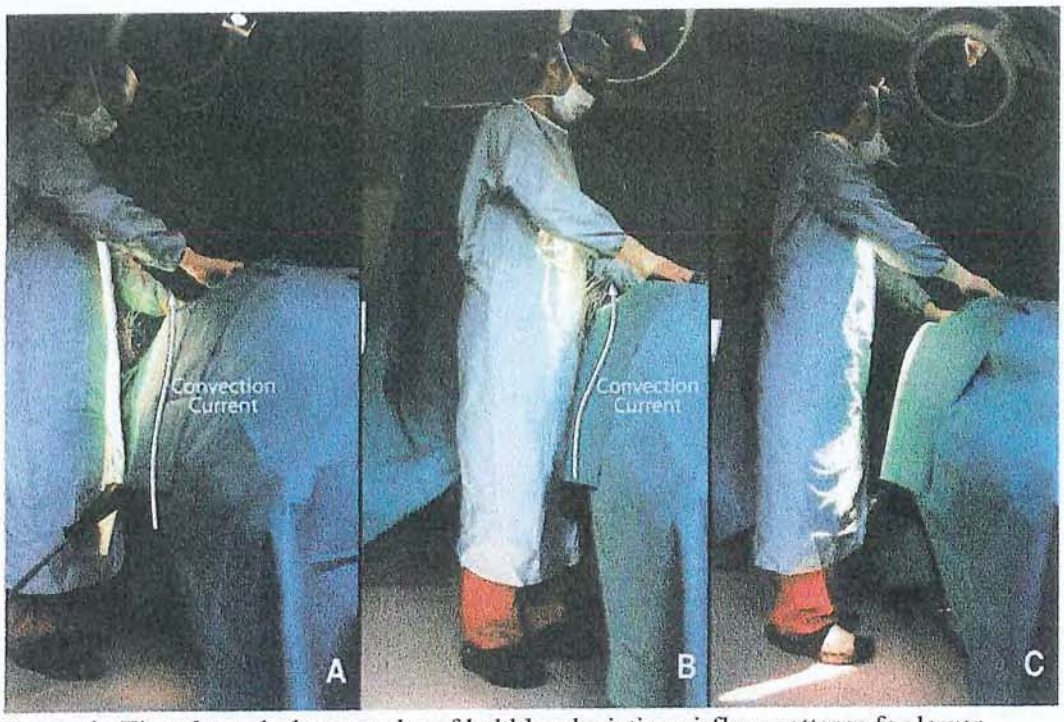

Figure 6: Time-lapsed-photography of bubbles depicting airflow patterns for lower lumbar spinal implant procedure with: (A & B) Forced air warming with resulting convection currents annotated and (C) conductive fabric warming.

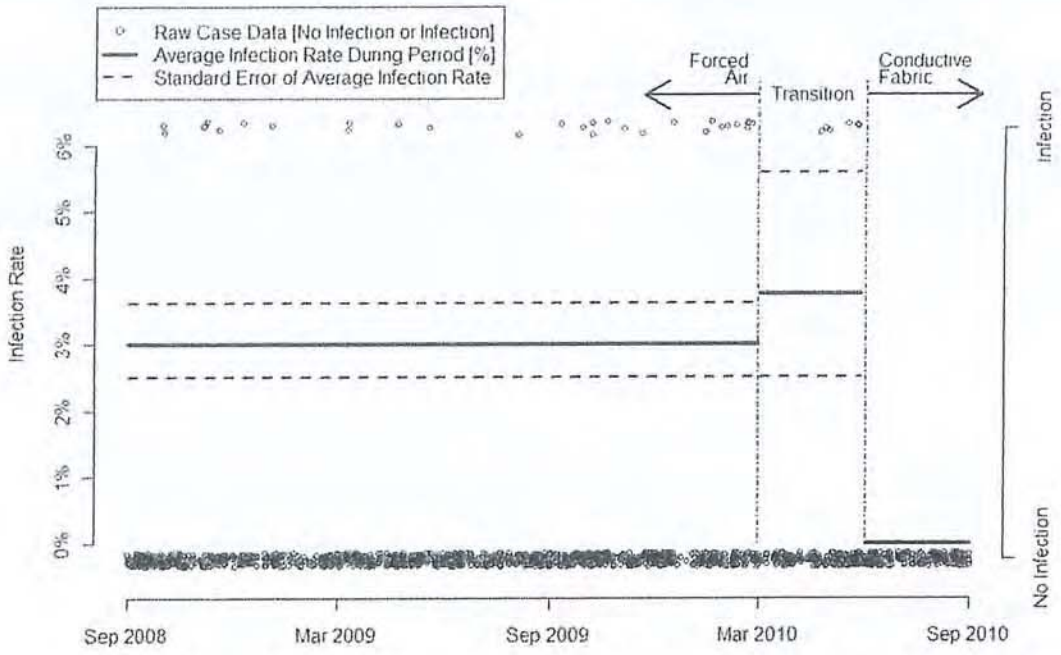

Figure 7: Infection data for n=1290 joint replacement cases with the outcome plotted on the right hand axis (data is jittered to avoid overprinting). Average infection rates for each period (Forced air, Transition, or Conductive Fabric) are plotted on the left hand axis. Standard error of the mean was estimated using logistic regression.

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Forced Air Warming and Ultra-Clean Ventilation Do Not Mix: The effect of excess vented heat on clean-airflow patterns.

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Key words: surgical site infection, forced air warming, laminar air flow, ultra clean ventilation, operating room environmental contamination, operating room ventilation, patient warming, hip replacement, knee replacement, arthroplasty.

Abstract

Introduction: Ultra-clean ventilation is designed to protect the surgical site from airborne pathogens. However, ventilation performance is fragile and depends critically on airflow volumes and temperature gradients. Patient warming systems represent a disruption risk via the excess heat they release. Therefore, we compared the effects of two patient warming systems – (1) conductive fabric and (2) forced air – on clean-airflow patterns over the surgical site during simulated hip replacement and spinal procedures.

Methods: A mannequin was draped for (1) a hip replacement and (2) a lumbar spinal implant in a partial-walled ultra-clean theatre. Neutral buoyancy detergent bubbles were released under the anaesthesia drape and at floor level to visualize air-currents and assess the mobilization of resident air into the clean-airflow over the surgical site. For the hip replacement, a randomized design assessed the effects upper-body warming system and anaesthesia drape height on bubbles reaching the surgical site. For the spinal surgery, the effect of the lower-body warming system was assessed with time-lapsed-photography of bubbles. Lastly, joint sepsis rates were tracked for a 2 year period over which a change from forced air to conductive fabric was implemented.

Results: For the hip replacement, bubble counts were significantly higher for forced air than conductive fabric for laid-down (3 versus 0; $p=0.010$) and half-height (68 versus 0; $p<0.001$) anaesthesia draping; differences for full-height draping were insignificant (1 versus 0; $p=0.283$). For the spinal surgery, time-lapsed-photography showed forced air to establish upwards convection currents that transported floor air into the surgical site; this convection current was not present with conductive fabric. Joint sepsis infection rates were reduced after the implementation of conductive fabric warming (0% for n=161) versus prior rates with forced air (3.0% for n=936).

Conclusion: Excess heat from forced air warming disrupted clean-airflow patterns over the surgical site and generated upward convection currents, which transported non-sterile air from the floor and the anaesthesia side of the drape into the surgical site; conductive fabric warming had no such effects. Observation of joint sepsis rates suggests an empirical reduction in infection with conductive fabric warming in orthopaedics.

Number of words: 339

Introduction

Although most famously remembered for pioneering the hip arthroplasty, Sir John Charnley was among the first to recognize the critical role of operating theatre (OT) ventilation in preventing joint sepsis. Charnley postulated that the "surgical implant might provide a nidus for the growth of airborne bacteria which ordinarily are accepted as non-pathogenic."[1] Research efforts confirmed Charnley's insights through animal studies[2] and a national clinical trial involving over 8000 operations demonstrating the efficacy of clean air for the reduction of arthroplasty infection rates.[3] As such, ultra-clean ventilation became the standard for orthopaedic procedures. Ultra-clean ventilation protects the surgical site from airborne contamination through the constant delivery of a downward uniform velocity (0.3 to 0.5 m/s) highly filtered (>99.997%) airflow.[4] However, the performance of ultra-clean ventilation depends critically on air-flow volumes and proper temperature gradients, the latter of which may be disrupted by excess heat released from patient warming devices.

The vented airflow from forced air warming is released at 43°C, which is often 20°C above ambient OT conditions.[5,6] The release of such thermal energy has the potential to establish temperature gradients that impede the downward velocity of the OT ventilation airflows. Further, reductions in downward flow velocity have been shown to increase contaminant entrainment into the surgical site.[7] Moreover, the release of excess heat may generate convection currents that rise against the downward airflows and mobilize non-sterile floor-level air into the surgical site.

Air-free alternatives, such as conductive fabric warming, have been developed that are comparably effective to forced air for the prevention of surgical hypothermia.[8-14] These alternatives have much higher thermal efficiencies than forced air warming and, therefore, release only a fraction of the excess heat.[6] As such, there is a need to critically assess the impact of forced air warming versus air-free alternatives on ultra-clean ventilation performance. Specifically, we compared the effects of (1) conductive fabric and (2) forced air warming on clean-airflow patterns over the surgical site in a partial-walled ultra-clean OT during two procedures representing the variety of implantable

operations typically encountered: 1) a hip replacement with upper-body warming, and 2) a lumbar spinal surgery with lower-body warming. Ventilation airflow patterns were visualized using neutrally buoyant detergent bubbles and observational data on joint sepsis rates were compared for the period each warming device was in clinical use.

Methods

Ultra-Clean Operating Theatre Characteristics:

Experiments were carried out in a partial-walled ultra-clean OT (ExFlow 90, Howorth, United Kingdom) used for orthopaedic and spinal surgery in the United Kingdom. Validation and verification checks per HTM 2025 showed the OT airflows to be within specification and having a mean velocity of 0.44 m/s two-meters off the floor, which is above the threshold required by the standards (0.38 m/s). However, a slight airflow imbalance was detected during validation testing due to the location of the theatre prep room that affected the results of a single particle entrainment test; entrainment values were 12% at that location, which marginally exceeded the recommended threshold of 10%. This slight discrepancy was unlikely to have any effect on the results of the study. Further, smoke testing detected normal airflow patterns under the canopy and the OT passed microbial contamination testing.

Airflow Visualization Procedures:

High intensity lighting was used to illuminate neutrally buoyant detergent bubbles having a 4 mm average diameter (referred to herein as "bubbles"). "Bubbles" were produced by a bubble generator (Sage Action, Ithaca, NY), which utilized a helium-mixed air supply, detergent, and centripetal bubble size classification filter. The bubble generator is specifically designed and validated for the visualization of air currents.[15] For photography, a digital camera (500D, Canon, Surrey, UK) was employed and shutter exposure time was set to ¼ of a second for time-lapsed-photography.

Experimental Setup: Hip Replacement

A mannequin was laid in the lateral position on an operating table and draped with a 3-piece orthopaedic kit (Molnlycke Health Care, Manchester, UK) in accordance with standard protocols (**Fig 1**). A surgeon, dressed in occlusive clothing with head gear (T4, Stryker, Kalamazoo, MI), and an anaesthesiologist stood motionless in front of the surgical site and behind the anaesthesia screen. At the head of the operating table, the surgical drape was either: 1) clipped to the ceiling to create a barrier between the surgical site and anaesthesia area (full-drape); 2) clipped to IV poles and raised 0.75 meters above

the operating table (half-drape); or 3) laid-down over the mannequin's head (laid-down). The experimental upper-body warming treatment was introduced under the drape and was either: 1) a torso forced air blanket (Bair Hugger Model 540, Arizant Healthcare, Eden Prairie, MN); or 2) a torso conductive fabric blanket (Hot Dog Model B110, Augustine Temperature Management, Eden Prairie, MN). The blankets were powered by standard controllers set to 43°C (conductive fabric - Model WC02, Augustine Temperature Management; forced air - Model 750, Arizant Healthcare). "Bubbles" were introduced at the neck of the mannequin to track under-drape resident air movements in the region where the excess patient warming heat was being released.

Experimental Setup: Lumbar Spinal Procedure

The same mannequin was laid in the prone position on the operating table and four drapes were arranged in a "square" configuration (Molnlycke Health Care) with the anaesthesia screen at full-height in accordance with standard protocols (**Fig 2**). A single surgeon stood motionless next to the surgical site for all experiments. The experimental lower-body warming treatment was introduced under the drape and was either: 1) a lower-body forced air blanket (Bair Hugger Model 525, Arizant Healthcare); or 2) a lower-body conductive fabric blanket (Hot Dog Model B103, Augustine Temperature Management). The blankets were powered by the same controllers as listed above set to 43°C. "Bubbles" were introduced at floor level between the surgeon's body and the operating room table in the region where the patient warming excess heat was being released.

Sampling Procedures

Hip Replacement: Bubble counts over the surgical site were measured for each experimental treatment using a sequence of 5 photographs taken at 10 second intervals. The number of bubbles reaching the surgical site was determined by counting the number of bubbles in a 0.5 by 0.5 meter region over the surgical site in each photograph (**Fig 3**).
Lumbar Spinal Procedure: Time-lapsed-photography was chosen over the use of bubble counts to show differences in ventilation performance between patient warming systems given the significant change in observed surgical site airflow patterns (see **Results**).

Experimental Design

Hip Arthroplasty: A replicated (n=2) $3^1 2^1$ full factorial design was employed to assess changes in bubble counts over the surgical site. The experimental factors considered were: 1) anaesthesia screen: laid-down, half-screen, or full-screen; and 2) patient warming device: conductive fabric or forced air.

Lumbar Spinal Procedure: No design was employed or necessary to demonstrate the difference in ventilation performance between forced air and conductive fabric patient warming systems (see **Results**).

Joint Sepsis Data

Joint sepsis data was collected for primary hip and knee replacement procedures performed at the hospital during the 2-year period prior to the study, with dates comprising 9/1/2008 to 9/1/2010. Infection was diagnosed by full time surgical site infection nurses according to UK health protection agency criteria for deep surgical site infection.[16] A transition in patient warming systems from forced air to conductive fabric was made in all four orthopaedic theatres starting 3/1/2010 and ending 6/1/2010.

Statistical Analysis

A Poisson regression model was fitted to the hip replacement data having the sum of bubble counts for each experimental run (5 pictures) as the response and the two factors identified in the experimental design as predictors (including interaction). Reported values are predicted means (± standard error of the mean) for experimental factor combinations. Wald tests were used for significance.

A logistic regression model was fitted to the joint sepsis data having infection as the response and the period (forced air, transition, and conductive fabric warming) as predictors. Reported values are predicted mean infection rates (± standard error of the mean) for each period. Wald tests were used for significance.

Results

Hip Replacement:

The number of bubbles reaching the surgical site measured the degree to which patient warming excess heat mobilized resident under-drape air over the anaesthesia screen and into the surgical site. Bubble counts per photograph (**Fig 4**) suggest that forced air warming generated sufficient excess heat to mobilize resident under-drape air over the anaesthesia screen. In contrast, conductive fabric warming did not generate sufficient excess heat to have the same mobilizing effect. Further, surgical drape position appeared to have a large effect on resident under-drape air mobilization into the surgical site for forced air warming, with the half-drape configuration resulting in the largest degree of resident-air mobilization.

Differences in the sum of bubble counts for each experimental run (**Fig 5**) were significant between conductive fabric and forced air warming for the drape configurations of half-drape (0 versus 68, $p<0.001$) and laid-down (0 versus 3, $p=0.010$); differences for full-drape (0 versus 1, $p=0.283$) were insignificant. It was necessary to model the sum of bubble counts for statistical inference; otherwise observations would not be independent.

Lumbar Spinal Procedure:

Time-lapsed-photography showed forced air warming excess heat to generate hot-air convection currents that transported large quantities of floor-level resident air upwards and into the surgical site (**Fig 6**). These convection currents appeared to form in the space between the surgeon's body and the operating room table. In contrast, conductive fabric warming did not generate sufficient excess heat to establish such convection currents. Instead, with conductive fabric warming ventilation airflow patterns followed the intended path - downwards and away from the surgical site.

Joint Sepsis Rates:

A 2-year observation of deep infection in joint replacement revealed a significant reduction ($p=0.007$) in joint sepsis rates for the period conductive fabric warming was in

clinical use versus forced air warming, with average infection rates of 0.0% (n=165) versus 3.0% (n=965), respectively (**Fig 7**). The reported p-value is the probability of observing 0 infections in 165 cases given a 3.0% infection rate and a binomial distribution, since model asymptotics are unstable in the region where p≈0. There was a 3 month transition period where both patient warming devices were used in the orthopaedic theatres having an infection rate of 3.7% (n=160), which was not significantly different from the infection rate of 3.0% during the forced air warming period (p=0.62). It should be noted that changes to both antibiotic regimes and thromboprophylaxis were made over this period and, thus, may be confounding factors.[17]

Discussion

This study compared the effects of two patient warming systems, forced air and conductive fabric, on ventilation performance in an ultra-clean operating theatre during hip replacement and spinal procedures. Forced air warming excess heat was found to generate convection currents that disrupted clean-airflow patterns over the surgical site during both procedures. In contrast, conductive fabric warming released minimal excess heat and was shown to have no effect on ventilation performance in either procedure. The results also showed forced air warming excess heat to mobilize resident air from typically non-sterile areas (floor & under the anaesthesia drape) into the surgical site, a finding that may have implications regarding surgical site sterility.

Perhaps the most striking finding was the detection of hot-air convection currents originating from where the "mass-flow" of hot air exhausted the forced air warming blanket: for the hip replacement with upper-body warming, convection currents formed near the mannequin's head; for the spinal implant with lower-body warming, convection currents formed along the lower drape edge by the surgeon's legs. The formation of such convection currents may, at first, appear to be theoretically unsupported since forced air warming exhausts a heated airflow of only 40 cubic feet per minute into a ventilation environment having an airflow of 6000 cubic feet per minute.[18] However, one must also consider the effects of surgical lighting, drapes, and personnel on ventilation

performance, all of which create localized airflow disturbances that aid in convection current formation.

Prior research in ultra-clean ventilation theatres has shown surgical lighting to be a significant source of ventilation disruption through the downstream wake and associated recirculation zone.[15] In our study, the use of "bubbles" allowed us to visualize this recirculation zone, which was found to extend about 1 meter below the body of each surgical light. "Bubbles" and, thus, resident air reaching this zone tended to remain suspended in this vortex for some time. The presence of a raised anaesthesia drape was shown to further magnify the size and effect of this vortex, for the drape blocked the natural passage of air out of the ventilation field and created a "still zone" adjacent to the vortex. Lastly, the presence of a surgeon or anesthaestist near this "still zone" created an additional ventilation flow blockage[19] resulting in a situation where even the slightest movements adversely impacted the natural airflow patterns over the surgical site. Under such fragile conditions, the "mass-flow" of hot forced air warming exhaust was sufficiently buoyant to push upwards and into this locally compromised ventilation region.

The clinical concern regarding the formation of such convection currents is two-fold. First, these currents oppose the natural clean-airflow patterns that are intended to sweep contaminants down and away from the surgical site.[20] Thus, contaminants released in the vicinity of the surgical site are less likely to be cleared. Second, the upward mobilization of floor-level and under-drape air could potentially compromise the sterility of the surgical site, since resident air from these locations is typically laden with pathogens shed from the surgical staff.[21] Even small elevations in contaminant exposure could be of clinical significance given that airborne derived infection risks are exponentially magnified with implantable procedures.[22] Empirical support for the concept that observed convection currents resulted in increased surgical site contaminant exposure can be found in the observed reduction in hospital hip and knee joint replacement infection rates when a switch from forced air to conductive fabric warming was implemented. However, this infection data is observational in nature and does not prove that such a

relationship exists since we were unable to control for other measures instituted by the hospital over the 2-year period.

Further, the present study is somewhat limited in that we assessed the movements of "bubbles" as a surrogate for the movement of pathogenic contaminants. Thus, the clinical relevance of our findings depend on two assumptions: 1) that floor-level and under-drape air is non-sterile; and 2) that airborne contaminant concentrations from these locations represent a significant infection risk relative to other contamination sources. Moreover, the entire field of prior research assessing forced air warming excess heat and changes in airborne pathogen levels during implantable procedures is limited to a single orthopaedic study, in which forced air warming resulted in elevated microbial counts over the surgical site.[23] However, the contamination increase was deemed to be far less than that resulting from personnel movements and such increases did not exceed recommended bacterial levels. Yet, it is unknown how these results translate over the range of implantable procedures. Even minor differences in factors such as surgical draping, procedural practices, and theatre dress are likely to have large effects on both floor-level and under-drape contaminant levels and the dynamics of convection current formation.

National studies on the benefits of ultra-clean ventilation may provide a better indication as to the impact of forced air warming on contaminant mobilization for they take into account the full range of surgical draping, procedural practices, and theater dress. Over the past 10 years, these studies have shown either a trend towards[24] or significantly higher[25,26] infection rates. The mobilization of non-sterile air with forced air warming may be the explanatory factor, since historical studies[1,3] on laminar flow ventilation conducted before the introduction of forced air warming showed clear infection reduction benefits.

Until the effects of forced air warming excess heat on ventilation disruption can be fully evaluated in regards to affecting the sterility of the surgical site, the use of air-free patient

warming alternatives might be recommended for implant procedures carried out in ultra-clean theatres.

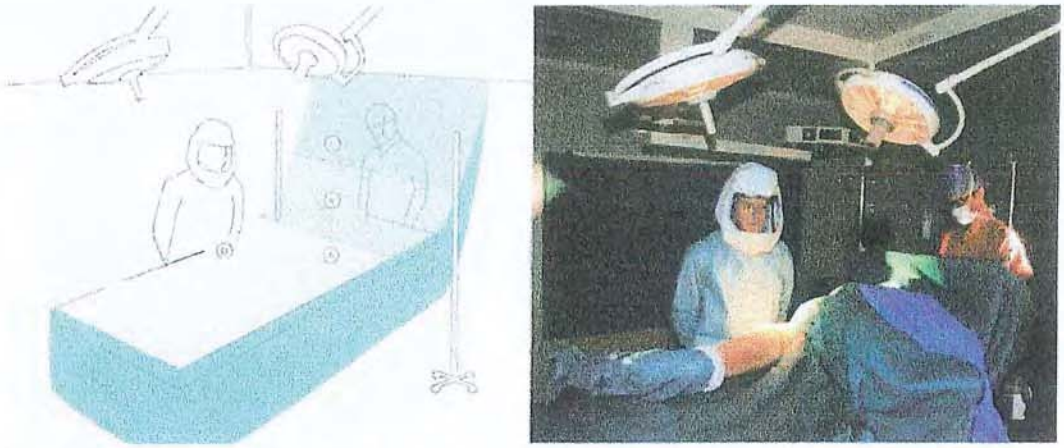

Figure 1: Hip replacement setup with upper-body warming, showing: surgical drape positions of laid-down (A), half-drape (B), and full-drape (C) and surgical site location (D)

Figure 2: Lumbar spinal setup with lower-body warming and full-drape, showing: surgical site location (A).

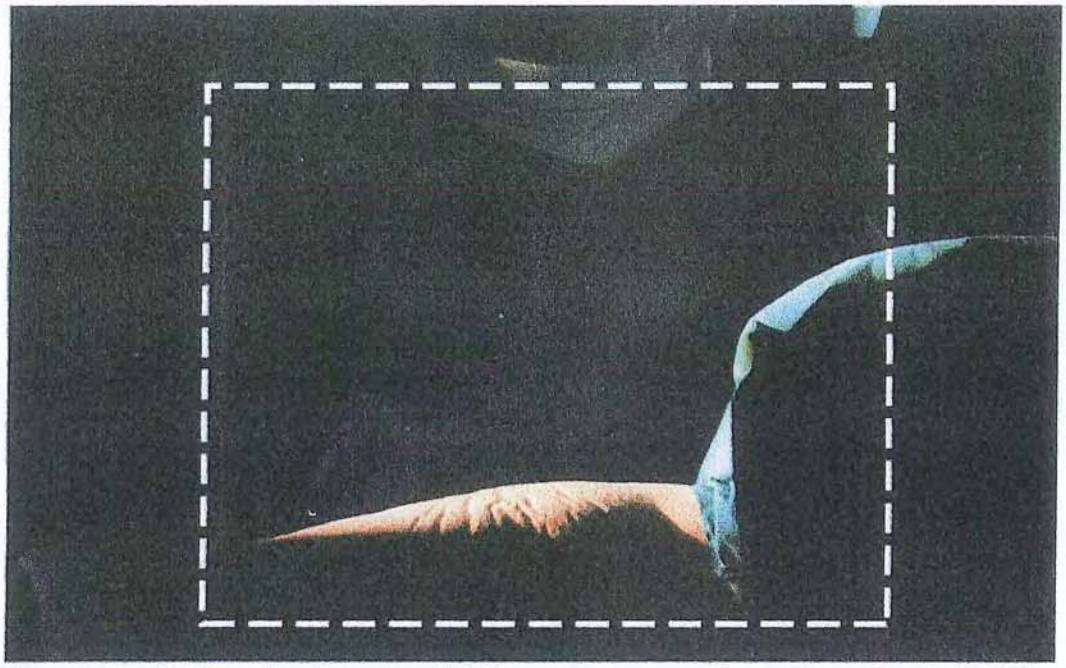

Figure 3: Definition of region where bubble counts were performed over the surgical site for hip replacement with upper-body warming. A picture shows bubbles (white steaks) appearing in the photograph for the experimental setup of forced air warming and half-drape.

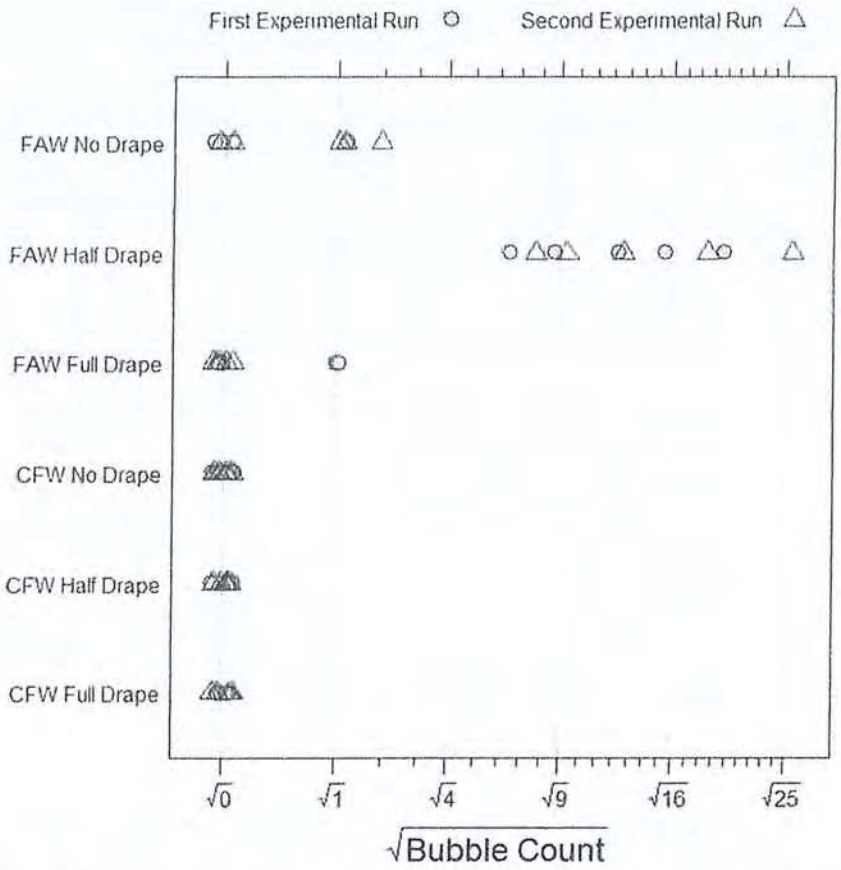

Figure 4: Bubble counts over the surgical site for each photograph (data is jittered to avoid overprinting). 5 photographs were taken for each experimental run. Abbreviations: FAW, Forced Air Warming; CFW, Conductive Fabric Warming.

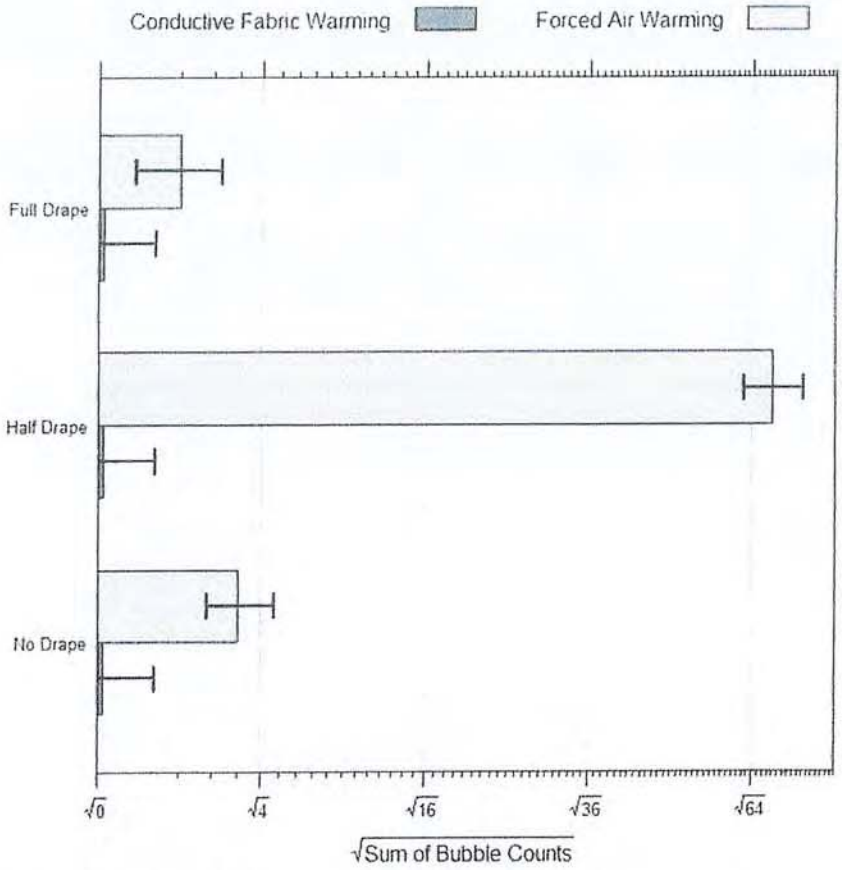

Figure 5: Average bubble count for experimental runs when the bubble counts are summed over the 5 photographs (±Standard Error of the Mean).

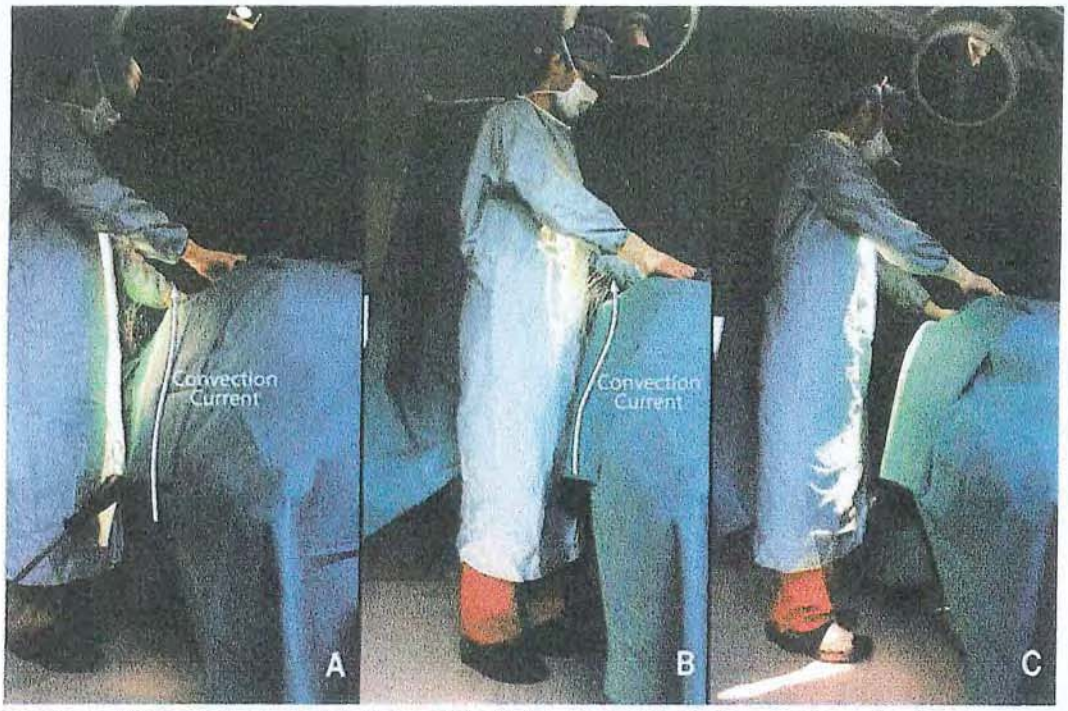

Figure 6: Time-lapsed-photography of bubbles depicting airflow patterns for lower lumbar spinal implant procedure with: (A & B) Forced air warming with resulting convection currents annotated and (C) conductive fabric warming.

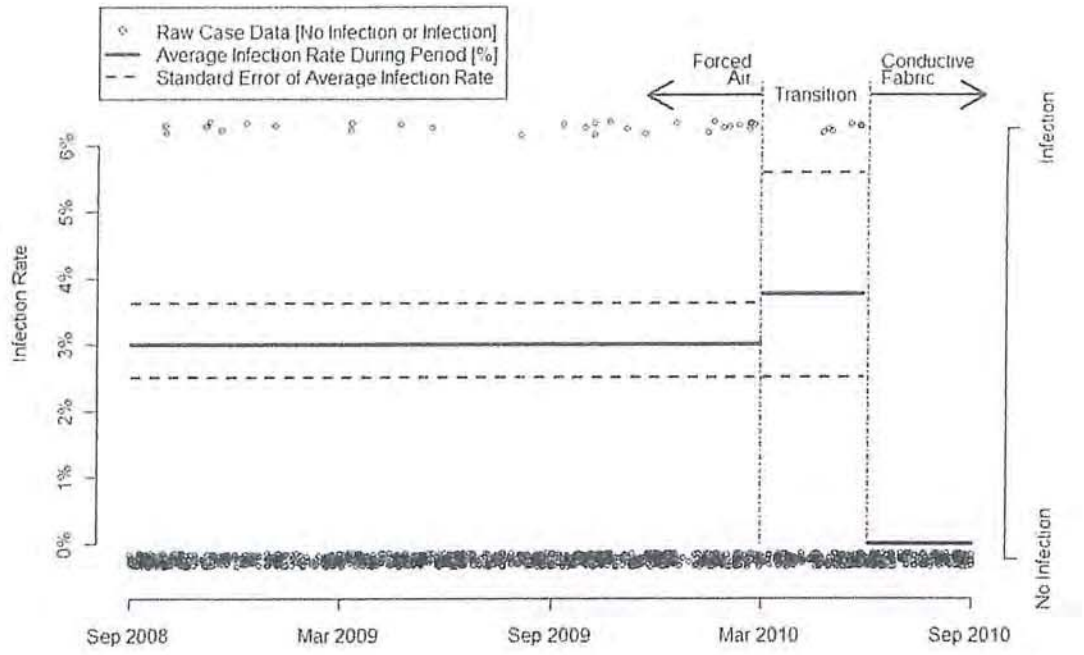

Figure 7: Infection data for n=1290 joint replacement cases with the outcome plotted on the right hand axis (data is jittered to avoid overprinting). Average infection rates for each period (Forced air, Transition, or Conductive Fabric) are plotted on the left hand axis. Standard error of the mean was estimated using logistic regression.

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Forced Air Warming and Ultra-Clean Ventilation Do Not Mix: The effect of excess vented heat on clean-airflow patterns.

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Key words: surgical site infection, forced air warming, laminar air flow, ultra clean ventilation, operating room environmental contamination, operating room ventilation, patient warming, hip replacement, knee replacement, arthroplasty.

Abstract

Introduction: Ultra-clean ventilation is designed to protect the surgical site from airborne pathogens. However, ventilation performance is fragile and depends critically on airflow volumes and temperature gradients. Patient warming systems represent a disruption risk via the excess heat they release. Therefore, we compared the effects of two patient warming systems – (1) conductive fabric and (2) forced air – on clean-airflow patterns over the surgical site during simulated hip replacement and spinal procedures.

Methods: A mannequin was draped for (1) a hip replacement and (2) a lumbar spinal implant in a partial-walled ultra-clean theatre. Neutral buoyancy detergent bubbles were released under the anaesthesia drape and at floor level to visualize air-currents and assess the mobilization of resident air into the clean-airflow over the surgical site. For the hip replacement, a randomized design assessed the effects upper-body warming system and anaesthesia drape height on bubbles reaching the surgical site. For the spinal surgery, the effect of the lower-body warming system was assessed with time-lapsed-photography of bubbles. Lastly, joint sepsis rates were tracked for a 2 year period over which a change from forced air to conductive fabric was implemented.

Results: For the hip replacement, bubble counts were significantly higher for forced air than conductive fabric for laid-down (3 versus 0; $p=0.010$) and half-height (68 versus 0; $p<0.001$) anaesthesia draping; differences for full-height draping were insignificant (1 versus 0; $p=0.283$). For the spinal surgery, time-lapsed-photography showed forced air to establish upwards convection currents that transported floor air into the surgical site; this convection current was not present with conductive fabric. Joint sepsis infection rates were reduced after the implementation of conductive fabric warming (0% for n=161) versus prior rates with forced air (3.0% for n=936).

Conclusion: Excess heat from forced air warming disrupted clean-airflow patterns over the surgical site and generated upward convection currents, which transported non-sterile air from the floor and the anaesthesia side of the drape into the surgical site; conductive fabric warming had no such effects. Observation of joint sepsis rates suggests an empirical reduction in infection with conductive fabric warming in orthopaedics.

Number of words: 339

Introduction

Although most famously remembered for pioneering the hip arthroplasty, Sir John Charnley was among the first to recognize the critical role of operating theatre (OT) ventilation in preventing joint sepsis. Charnley postulated that the "surgical implant might provide a nidus for the growth of airborne bacteria which ordinarily are accepted as non-pathogenic."[1] Research efforts confirmed Charnley's insights through animal studies[2] and a national clinical trial involving over 8000 operations demonstrating the efficacy of clean air for the reduction of arthroplasty infection rates.[3] As such, ultra-clean ventilation became the standard for orthopaedic procedures. Ultra-clean ventilation protects the surgical site from airborne contamination through the constant delivery of a downward uniform velocity (0.3 to 0.5 m/s) highly filtered (>99.997%) airflow.[4] However, the performance of ultra-clean ventilation depends critically on air-flow volumes and proper temperature gradients, the latter of which may be disrupted by excess heat released from patient warming devices.

The vented airflow from forced air warming is released at 43°C, which is often 20°C above ambient OT conditions.[5,6] The release of such thermal energy has the potential to establish temperature gradients that impede the downward velocity of the OT ventilation airflows. Further, reductions in downward flow velocity have been shown to increase contaminant entrainment into the surgical site.[7] Moreover, the release of excess heat may generate convection currents that rise against the downward airflows and mobilize non-sterile floor-level air into the surgical site.

Air-free alternatives, such as conductive fabric warming, have been developed that are comparably effective to forced air for the prevention of surgical hypothermia.[8-14] These alternatives have much higher thermal efficiencies than forced air warming and, therefore, release only a fraction of the excess heat.[6] As such, there is a need to critically assess the impact of forced air warming versus air-free alternatives on ultra-clean ventilation performance. Specifically, we compared the effects of (1) conductive fabric and (2) forced air warming on clean-airflow patterns over the surgical site in a partial-walled ultra-clean OT during two procedures representing the variety of implantable

operations typically encountered: 1) a hip replacement with upper-body warming, and 2) a lumbar spinal surgery with lower-body warming. Ventilation airflow patterns were visualized using neutrally buoyant detergent bubbles and observational data on joint sepsis rates were compared for the period each warming device was in clinical use.

Methods

Ultra-Clean Operating Theatre Characteristics:

Experiments were carried out in a partial-walled ultra-clean OT (ExFlow 90, Howorth, United Kingdom) used for orthopaedic and spinal surgery in the United Kingdom. Validation and verification checks per HTM 2025 showed the OT airflows to be within specification and having a mean velocity of 0.44 m/s two-meters off the floor, which is above the threshold required by the standards (0.38 m/s). However, a slight airflow imbalance was detected during validation testing due to the location of the theatre prep room that affected the results of a single particle entrainment test; entrainment values were 12% at that location, which marginally exceeded the recommended threshold of 10%. This slight discrepancy was unlikely to have any effect on the results of the study. Further, smoke testing detected normal airflow patterns under the canopy and the OT passed microbial contamination testing.

Airflow Visualization Procedures:

High intensity lighting was used to illuminate neutrally buoyant detergent bubbles having a 4 mm average diameter (referred to herein as "bubbles"). "Bubbles" were produced by a bubble generator (Sage Action, Ithaca, NY), which utilized a helium-mixed air supply, detergent, and centripetal bubble size classification filter. The bubble generator is specifically designed and validated for the visualization of air currents.[15] For photography, a digital camera (500D, Canon, Surrey, UK) was employed and shutter exposure time was set to ¼ of a second for time-lapsed-photography.

Experimental Setup: Hip Replacement

A mannequin was laid in the lateral position on an operating table and draped with a 3-piece orthopaedic kit (Molnlycke Health Care, Manchester, UK) in accordance with standard protocols (**Fig 1**). A surgeon, dressed in occlusive clothing with head gear (T4, Stryker, Kalamazoo, MI), and an anaesthesiologist stood motionless in front of the surgical site and behind the anaesthesia screen. At the head of the operating table, the surgical drape was either: 1) clipped to the ceiling to create a barrier between the surgical site and anaesthesia area (full-drape); 2) clipped to IV poles and raised 0.75 meters above

the operating table (half-drape); or 3) laid-down over the mannequin's head (laid-down). The experimental upper-body warming treatment was introduced under the drape and was either: 1) a torso forced air blanket (Bair Hugger Model 540, Arizant Healthcare, Eden Prairie, MN); or 2) a torso conductive fabric blanket (Hot Dog Model B110, Augustine Temperature Management, Eden Prairie, MN). The blankets were powered by standard controllers set to 43°C (conductive fabric - Model WC02, Augustine Temperature Management; forced air - Model 750, Arizant Healthcare). "Bubbles" were introduced at the neck of the mannequin to track under-drape resident air movements in the region where the excess patient warming heat was being released.

Experimental Setup: Lumbar Spinal Procedure

The same mannequin was laid in the prone position on the operating table and four drapes were arranged in a "square" configuration (Molnlycke Health Care) with the anaesthesia screen at full-height in accordance with standard protocols (**Fig 2**). A single surgeon stood motionless next to the surgical site for all experiments. The experimental lower-body warming treatment was introduced under the drape and was either: 1) a lower-body forced air blanket (Bair Hugger Model 525, Arizant Healthcare); or 2) a lower-body conductive fabric blanket (Hot Dog Model B103, Augustine Temperature Management). The blankets were powered by the same controllers as listed above set to 43°C. "Bubbles" were introduced at floor level between the surgeon's body and the operating room table in the region where the patient warming excess heat was being released.

Sampling Procedures

Hip Replacement: Bubble counts over the surgical site were measured for each experimental treatment using a sequence of 5 photographs taken at 10 second intervals. The number of bubbles reaching the surgical site was determined by counting the number of bubbles in a 0.5 by 0.5 meter region over the surgical site in each photograph (**Fig 3**).
Lumbar Spinal Procedure: Time-lapsed-photography was chosen over the use of bubble counts to show differences in ventilation performance between patient warming systems given the significant change in observed surgical site airflow patterns (see **Results**).

Experimental Design

Hip Arthroplasty: A replicated (n=2) $3^1 2^1$ full factorial design was employed to assess changes in bubble counts over the surgical site. The experimental factors considered were: 1) anaesthesia screen: laid-down, half-screen, or full-screen; and 2) patient warming device: conductive fabric or forced air.

Lumbar Spinal Procedure: No design was employed or necessary to demonstrate the difference in ventilation performance between forced air and conductive fabric patient warming systems (see **Results**).

Joint Sepsis Data

Joint sepsis data was collected for primary hip and knee replacement procedures performed at the hospital during the 2-year period prior to the study, with dates comprising 9/1/2008 to 9/1/2010. Infection was diagnosed by full time surgical site infection nurses according to UK health protection agency criteria for deep surgical site infection.[16] A transition in patient warming systems from forced air to conductive fabric was made in all four orthopaedic theatres starting 3/1/2010 and ending 6/1/2010.

Statistical Analysis

A Poisson regression model was fitted to the hip replacement data having the sum of bubble counts for each experimental run (5 pictures) as the response and the two factors identified in the experimental design as predictors (including interaction). Reported values are predicted means (± standard error of the mean) for experimental factor combinations. Wald tests were used for significance.

A logistic regression model was fitted to the joint sepsis data having infection as the response and the period (forced air, transition, and conductive fabric warming) as predictors. Reported values are predicted mean infection rates (± standard error of the mean) for each period. Wald tests were used for significance.

Results

Hip Replacement:

The number of bubbles reaching the surgical site measured the degree to which patient warming excess heat mobilized resident under-drape air over the anaesthesia screen and into the surgical site. Bubble counts per photograph (**Fig 4**) suggest that forced air warming generated sufficient excess heat to mobilize resident under-drape air over the anaesthesia screen. In contrast, conductive fabric warming did not generate sufficient excess heat to have the same mobilizing effect. Further, surgical drape position appeared to have a large effect on resident under-drape air mobilization into the surgical site for forced air warming, with the half-drape configuration resulting in the largest degree of resident-air mobilization.

Differences in the sum of bubble counts for each experimental run (**Fig 5**) were significant between conductive fabric and forced air warming for the drape configurations of half-drape (0 versus 68, $p<0.001$) and laid-down (0 versus 3, $p=0.010$); differences for full-drape (0 versus 1, $p=0.283$) were insignificant. It was necessary to model the sum of bubble counts for statistical inference; otherwise observations would not be independent.

Lumbar Spinal Procedure:

Time-lapsed-photography showed forced air warming excess heat to generate hot-air convection currents that transported large quantities of floor-level resident air upwards and into the surgical site (**Fig 6**). These convection currents appeared to form in the space between the surgeon's body and the operating room table. In contrast, conductive fabric warming did not generate sufficient excess heat to establish such convection currents. Instead, with conductive fabric warming ventilation airflow patterns followed the intended path - downwards and away from the surgical site.

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A 2-year observation of deep infection in joint replacement revealed a significant reduction ($p=0.007$) in joint sepsis rates for the period conductive fabric warming was in

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This study compared the effects of two patient warming systems, forced air and conductive fabric, on ventilation performance in an ultra-clean operating theatre during hip replacement and spinal procedures. Forced air warming excess heat was found to generate convection currents that disrupted clean-airflow patterns over the surgical site during both procedures. In contrast, conductive fabric warming released minimal excess heat and was shown to have no effect on ventilation performance in either procedure. The results also showed forced air warming excess heat to mobilize resident air from typically non-sterile areas (floor & under the anaesthesia drape) into the surgical site, a finding that may have implications regarding surgical site sterility.

Perhaps the most striking finding was the detection of hot-air convection currents originating from where the "mass-flow" of hot air exhausted the forced air warming blanket: for the hip replacement with upper-body warming, convection currents formed near the mannequin's head; for the spinal implant with lower-body warming, convection currents formed along the lower drape edge by the surgeon's legs. The formation of such convection currents may, at first, appear to be theoretically unsupported since forced air warming exhausts a heated airflow of only 40 cubic feet per minute into a ventilation environment having an airflow of 6000 cubic feet per minute.[18] However, one must also consider the effects of surgical lighting, drapes, and personnel on ventilation

performance, all of which create localized airflow disturbances that aid in convection current formation.

Prior research in ultra-clean ventilation theatres has shown surgical lighting to be a significant source of ventilation disruption through the downstream wake and associated recirculation zone.[15] In our study, the use of "bubbles" allowed us to visualize this recirculation zone, which was found to extend about 1 meter below the body of each surgical light. "Bubbles" and, thus, resident air reaching this zone tended to remain suspended in this vortex for some time. The presence of a raised anaesthesia drape was shown to further magnify the size and effect of this vortex, for the drape blocked the natural passage of air out of the ventilation field and created a "still zone" adjacent to the vortex. Lastly, the presence of a surgeon or anesthaestist near this "still zone" created an additional ventilation flow blockage[19] resulting in a situation where even the slightest movements adversely impacted the natural airflow patterns over the surgical site. Under such fragile conditions, the "mass-flow" of hot forced air warming exhaust was sufficiently buoyant to push upwards and into this locally compromised ventilation region.

The clinical concern regarding the formation of such convection currents is two-fold. First, these currents oppose the natural clean-airflow patterns that are intended to sweep contaminants down and away from the surgical site.[20] Thus, contaminants released in the vicinity of the surgical site are less likely to be cleared. Second, the upward mobilization of floor-level and under-drape air could potentially compromise the sterility of the surgical site, since resident air from these locations is typically laden with pathogens shed from the surgical staff.[21] Even small elevations in contaminant exposure could be of clinical significance given that airborne derived infection risks are exponentially magnified with implantable procedures.[22] Empirical support for the concept that observed convection currents resulted in increased surgical site contaminant exposure can be found in the observed reduction in hospital hip and knee joint replacement infection rates when a switch from forced air to conductive fabric warming was implemented. However, this infection data is observational in nature and does not prove that such a

relationship exists since we were unable to control for other measures instituted by the hospital over the 2-year period.

Further, the present study is somewhat limited in that we assessed the movements of "bubbles" as a surrogate for the movement of pathogenic contaminants. Thus, the clinical relevance of our findings depend on two assumptions: 1) that floor-level and under-drape air is non-sterile; and 2) that airborne contaminant concentrations from these locations represent a significant infection risk relative to other contamination sources. Moreover, the bulk of prior research on the risks of forced air warming has either investigated ventilation disruption due to excess heat in conventional OTs[23,24] unsuitable for orthopaedic operations or evaluated microbial contamination buildup and emission issues.[25-29] Relevant research in ultra-clean OTs is limited to a single orthopaedic study in which forced air warming resulted in elevated microbial counts over the surgical site.[30] However, the contamination increase was deemed to be far less than that resulting from personnel movements and such increases did not exceed recommended bacterial levels. Yet, it is unknown how these results translate over the range of implantable procedures performed in ultra-clean OTs. Even minor differences in factors such as surgical draping, procedural practices, and theatre dress are likely to have large effects on both floor-level and under-drape contaminant levels and the dynamics of convection current formation.

National studies on the benefits of ultra-clean ventilation may provide a better indication as to the impact of forced air warming on contaminant mobilization for they take into account the full range of surgical draping, procedural practices, and theater dress. Over the past 10 years, these studies have shown either a trend towards[31] or significantly higher[32,33] infection rates. The mobilization of non-sterile air with forced air warming may be the explanatory factor, since historical studies[1,3] on laminar flow ventilation conducted before the introduction of forced air warming showed clear infection reduction benefits.

Until the effects of forced air warming excess heat on ventilation disruption can be fully evaluated in regards to affecting the sterility of the surgical site, the use of air-free patient

warming alternatives might be recommended for implant procedures carried out in ultra-clean theatres.

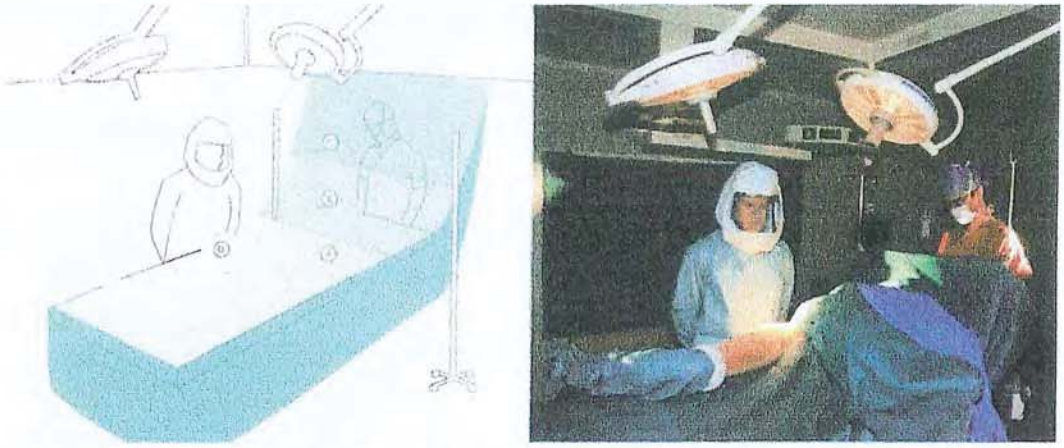

Figure 1: Hip replacement setup with upper-body warming, showing: surgical drape positions of laid-down (A), half-drape (B), and full-drape (C) and surgical site location (D)

Figure 2: Lumbar spinal setup with lower-body warming and full-drape, showing: surgical site location (A).

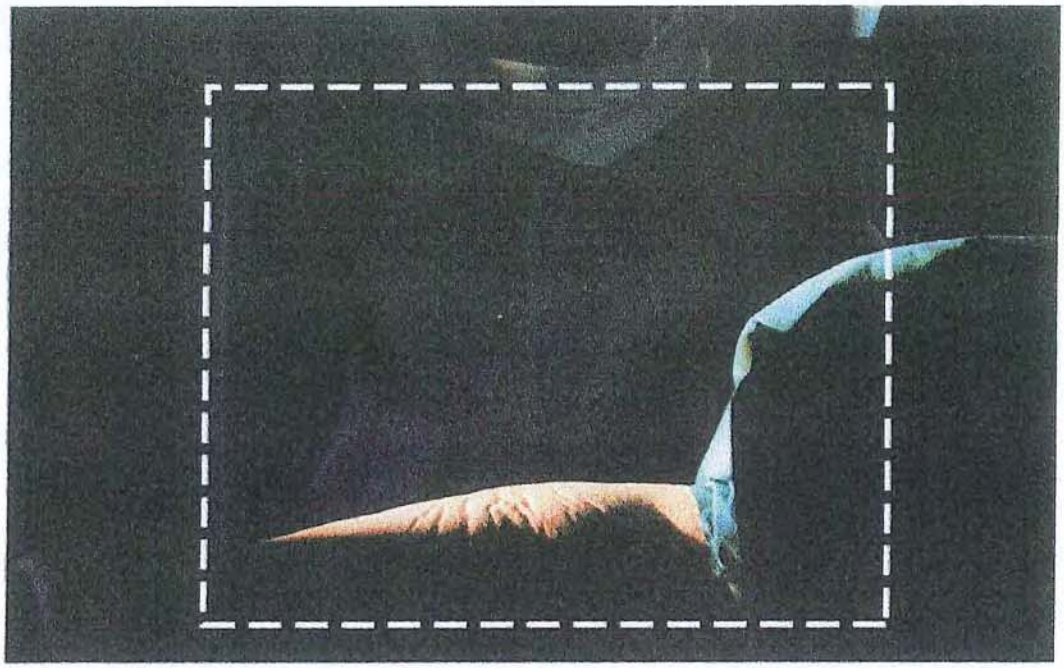

Figure 3: Definition of region where bubble counts were performed over the surgical site for hip replacement with upper-body warming. A picture shows bubbles (white steaks) appearing in the photograph for the experimental setup of forced air warming and half-drape.

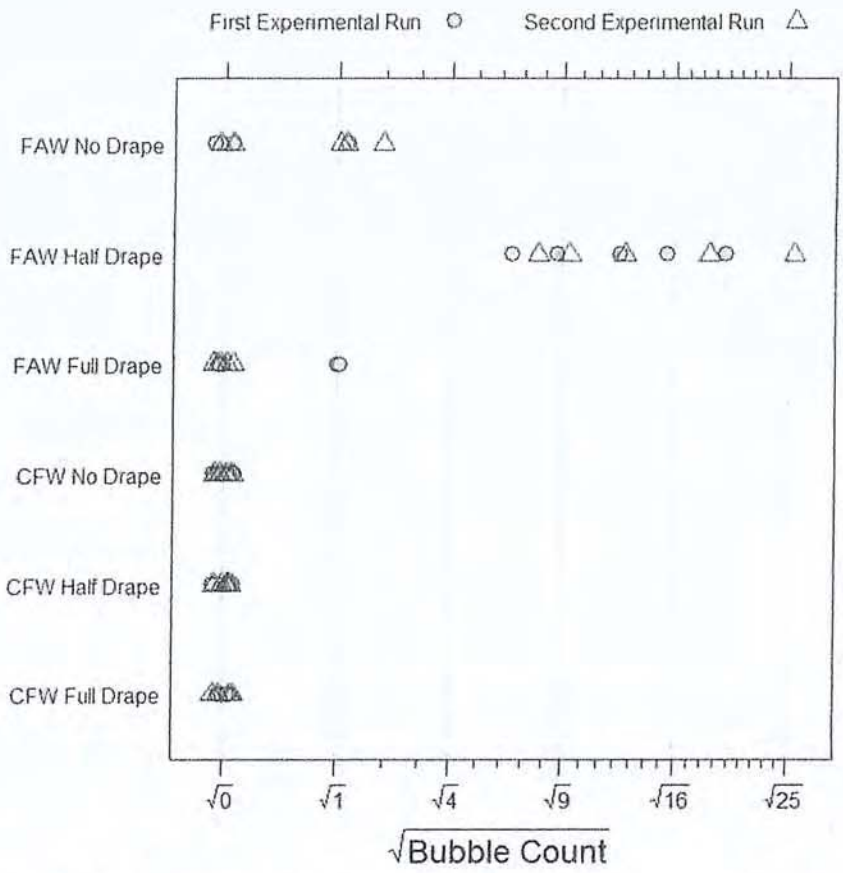

Figure 4: Bubble counts over the surgical site for each photograph (data is jittered to avoid overprinting). 5 photographs were taken for each experimental run. Abbreviations: FAW, Forced Air Warming; CFW, Conductive Fabric Warming.

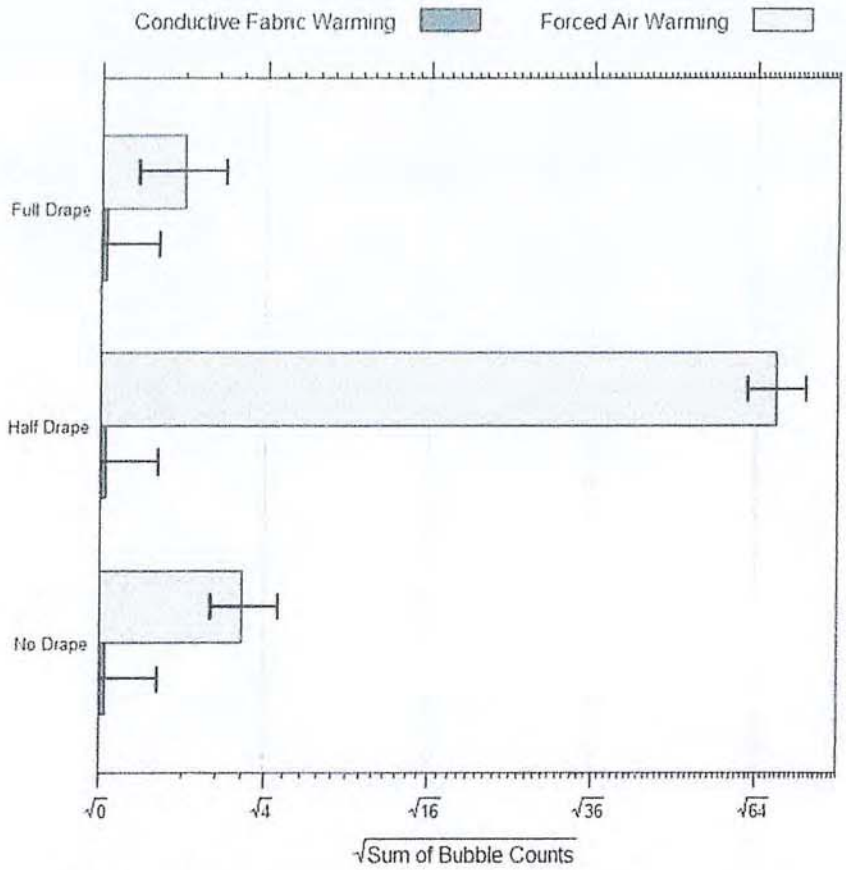

Figure 5: Average bubble count for experimental runs when the bubble counts are summed over the 5 photographs (±Standard Error of the Mean).

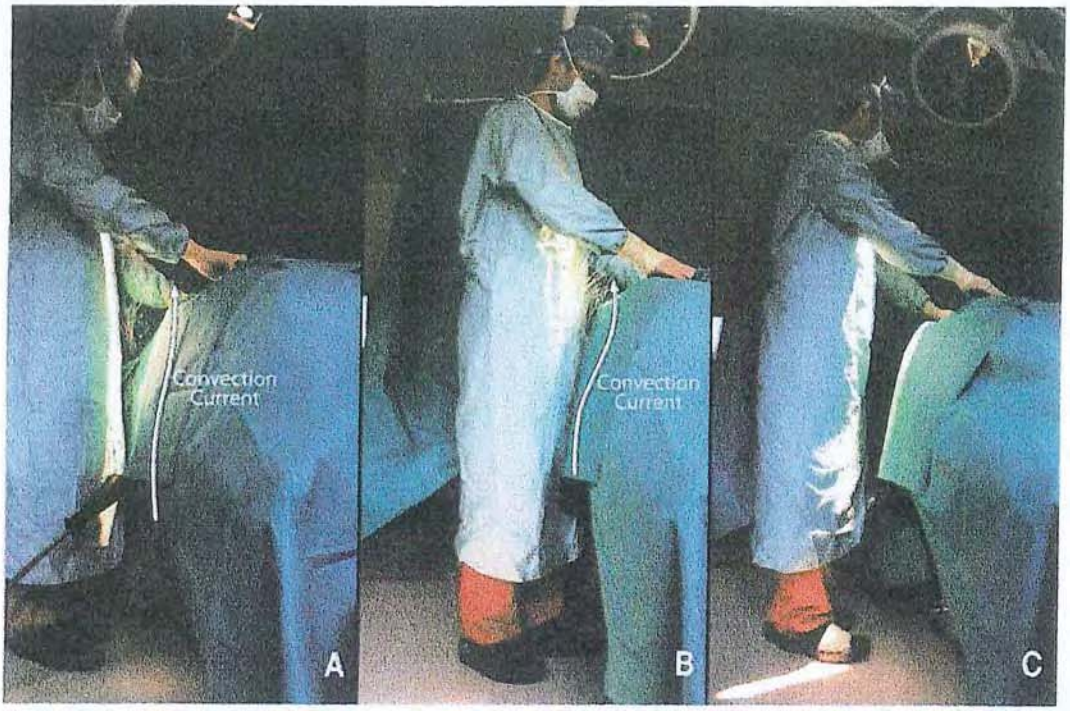

Figure 6: Time-lapsed-photography of bubbles depicting airflow patterns for lower lumbar spinal implant procedure with: (A & B) Forced air warming with resulting convection currents annotated and (C) conductive fabric warming.

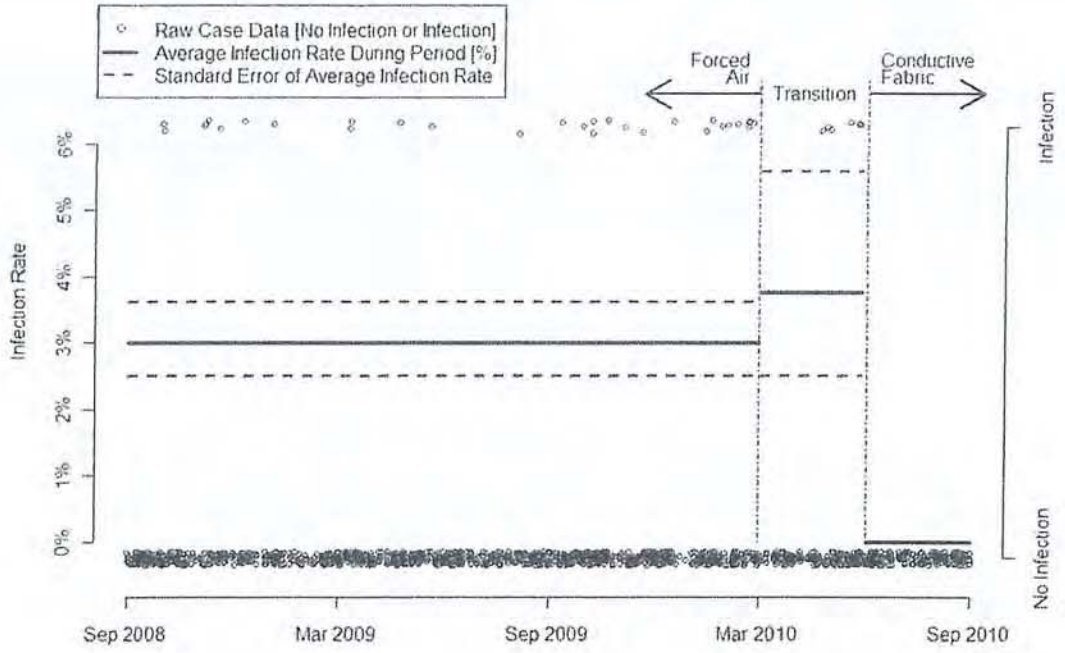

Figure 7: Infection data for n=1290 joint replacement cases with the outcome plotted on the right hand axis (data is jittered to avoid overprinting). Average infection rates for each period (Forced air, Transition, or Conductive Fabric) are plotted on the left hand axis. Standard error of the mean was estimated using logistic regression.

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Forced Air Warming and Ultra-Clean Ventilation Do Not Mix: The effect of excess vented heat on clean-airflow patterns.

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Key words: surgical site infection, forced air warming, laminar air flow, ultra clean ventilation, operating room environmental contamination, operating room ventilation, patient warming, hip replacement, knee replacement, arthroplasty.

Abstract

Introduction: Ultra-clean ventilation is designed to protect the surgical site from airborne pathogens. However, ventilation performance is fragile and depends critically on airflow volumes and temperature gradients. Patient warming systems represent a disruption risk via the excess heat they release. Therefore, we compared the effects of two patient warming systems – (1) conductive fabric and (2) forced air – on clean-airflow patterns over the surgical site during simulated hip replacement and spinal procedures.

Methods: A mannequin was draped for (1) a hip replacement and (2) a lumbar spinal implant in a partial-walled ultra-clean theatre. Neutral buoyancy detergent bubbles were released under the anaesthesia drape and at floor level to visualize air-currents and assess the mobilization of resident air into the clean-airflow over the surgical site. For the hip replacement, a randomized design assessed the effects of upper-body warming system and anaesthesia drape height on bubbles reaching the surgical site. For the spinal surgery, the effect of the lower-body warming system was assessed with time-lapsed-photography of bubbles. Lastly, joint sepsis rates were tracked for a 2-year period over which a change from forced air to conductive fabric was implemented.

Results: For the hip replacement, bubble counts were significantly higher for forced air than conductive fabric for laid-down (3 versus 0; $p = 0.010$) and half-height (68 versus 0; $p < 0.001$) anaesthesia draping; differences for full-height draping were insignificant (1 versus 0; $p = 0.283$). For the spinal surgery, time-lapsed-photography showed forced air to establish upwards convection currents that transported floor air into the surgical site; this convection current was not present with conductive fabric. Joint sepsis infection rates were reduced after the implementation of conductive fabric warming (0% for n=161) versus prior rates with forced air (3.0% for n=936).

Conclusion: Excess heat from forced air warming disrupted clean-airflow patterns over the surgical site and generated upward convection currents, which transported non-sterile air from the floor and the anaesthesia side of the drape into the surgical site; conductive fabric warming had no such effects. Observation of joint sepsis rates suggests an empirical reduction in infection with conductive fabric warming in orthopaedics.

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Introduction

Although most famously remembered for pioneering hip arthroplasty, Sir John Charnley was among the first to recognize the critical role of operating theatre (OT) ventilation in preventing joint sepsis. Charnley postulated that the "surgical implant might provide a nidus for the growth of airborne bacteria which ordinarily are accepted as non-pathogenic."[1] Research efforts confirmed Charnley's insights through animal studies[2] and a national clinical trial involving over 8000 operations demonstrated the efficacy of clean air for the reduction of arthroplasty infection rates.[3] As such, ultra-clean ventilation became the standard for orthopaedic procedures. Ultra-clean ventilation protects the surgical site from airborne contamination through the constant delivery of a downward uniform velocity (0.3 to 0.5 m/s) highly filtered (>99.997%) airflow.[4] However, the performance of ultra-clean ventilation depends critically on air-flow volumes and proper temperature gradients, the latter of which may be disrupted by excess heat released from patient warming devices.

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Forced air warming is commonly used in operating theatres (OTs) to ensure patient normothermia. The vented airflow from forced air warming is released at 43°C, which is often 20°C above ambient OT conditions.[5,6] The release of such thermal energy has the potential to establish temperature gradients that impede the downward velocity of the OT ventilation airflows. Additionally, reductions in downward flow velocity have been shown to increase contaminant entrainment into the surgical site.[7] Moreover, the release of excess heat may generate convection currents that rise against the downward airflows and mobilize non-sterile floor-level air into the surgical site.

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Air-free alternatives, such as conductive fabric warming, have been developed that are comparably effective to forced air for the prevention of surgical hypothermia.[8-14] These alternatives have much higher thermal efficiencies than forced air warming and, therefore, release only a fraction of the excess heat.[6] As such, there is a need to critically assess the impact of forced air warming versus air-free alternatives on ultra-clean ventilation performance. Specifically, we compared the effects of (1) conductive fabric and (2) forced air warming on clean-airflow patterns over the surgical site in a partial-

walled ultra-clean OT during two procedures representing the variety of implantable operations typically encountered: 1) a hip replacement with upper-body warming, and 2) a lumbar spinal surgery with lower-body warming. Ventilation airflow patterns were visualized using neutrally buoyant detergent bubbles and observational data on joint sepsis rates were compared for the period each warming device was in clinical use.

Methods

Ultra-Clean Operating Theatre Characteristics:

Experiments were carried out in a partial-walled ultra-clean OT (ExFlow 90, Howorth, United Kingdom) used for orthopaedic and spinal surgery in the United Kingdom. Validation and verification checks per HTM 2025 showed the OT airflows to be within specification and having a mean velocity of 0.44 m/s two-meters off the floor, which is above the threshold required by the standards (0.38 m/s). However, an insignificant airflow imbalance was detected during validation testing due to the location of the theatre prep room that affected the results of a single particle entrainment test; entrainment values were 12% at that location, which marginally exceeded the recommended threshold of 10%. This marginal discrepancy was unlikely to have any effect on the results of the study because smoke testing detected normal airflow patterns under the canopy and the OT passed microbial contamination testing.

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Airflow Visualization Procedures:

High intensity lighting was used to illuminate neutrally buoyant detergent bubbles having a 4 mm average diameter (referred to herein as "bubbles"). "Bubbles" were produced by a bubble generator (Sage Action, Ithaca, NY), which utilized a helium-mixed air supply, detergent, and centripetal bubble size classification filter. The bubble generator is specifically designed and validated for the visualization of air currents.[15] For photography, a digital camera (500D, Canon, Surrey, UK) was employed and shutter exposure time was set to ¼ of a second for time-lapsed-photography.

Experimental Setup: Hip Replacement

A mannequin was laid in the lateral position on an operating table and draped with a 3-piece orthopaedic kit (Molnlycke Health Care, Manchester, UK) in accordance with standard protocols (**Fig 1**). A surgeon, dressed in occlusive clothing with head gear (T4, Stryker, Kalamazoo, MI), and an anaesthesiologist stood motionless in front of the surgical site and behind the anaesthesia screen. At the head of the operating table, the surgical drape was either: 1) clipped to the ceiling to create a barrier between the surgical site and anaesthesia area (full-drape); 2) clipped to IV poles and raised 0.75 meters above

the operating table (half-drape); or 3) laid-down over the mannequin's head (laid-down). The experimental upper-body warming treatment was introduced under the drape and was either: 1) a torso forced air blanket (Bair Hugger Model 540, Arizant Healthcare, Eden Prairie, MN); or 2) a torso conductive fabric blanket (Hot Dog Model B110, Augustine Temperature Management, Eden Prairie, MN). The blankets were powered by standard controllers set to 43°C (conductive fabric - Model WC02, Augustine Temperature Management; forced air - Model 750, Arizant Healthcare). "Bubbles" were introduced at the neck of the mannequin to track under-drape resident air movements in the region where the excess patient warming heat was being released.

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Experimental Setup: Lumbar Spinal Procedure

The same mannequin was laid in the prone position on the operating table and four drapes were arranged in a "square" configuration (Molnlycke Health Care) with the anaesthesia screen at full-height in accordance with standard protocols (**Fig 2**). A single surgeon stood motionless next to the surgical site for all experiments. The experimental lower-body warming treatment was introduced under the drape and was either: 1) a lower-body forced air blanket (Bair Hugger Model 525, Arizant Healthcare); or 2) a lower-body conductive fabric blanket (Hot Dog Model B103, Augustine Temperature Management). The blankets were powered by the same controllers as listed above set to 43°C. "Bubbles" were introduced at floor level between the surgeon's body and the operating room table in the region where the patient warming excess heat was being released.

Sampling Procedures

Hip Replacement: Bubble counts over the surgical site were measured for each experimental treatment using a sequence of 5 photographs taken at 10 second intervals. The number of bubbles reaching the surgical site was determined by counting the number of bubbles in a 0.5 by 0.5 meter region over the surgical site in each photograph (**Fig 3**).

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Lumbar Spinal Procedure: Time-lapsed-photography was chosen over the use of bubble counts to show differences in ventilation performance between patient warming systems given the significant change in observed surgical site airflow patterns (see **Results**).

Experimental Design

Hip Arthroplasty: A replicated (n=2) $3^1 2^1$ full factorial design was employed to assess changes in bubble counts over the surgical site. The experimental factors considered were: 1) anaesthesia screen: laid-down, half-screen, or full-screen; and 2) patient warming device: conductive fabric or forced air.

Lumbar Spinal Procedure: No design was employed or necessary to demonstrate the difference in ventilation performance between forced air and conductive fabric patient warming systems (see **Results**).

Joint Sepsis Data

Joint sepsis data was collected for primary hip and knee replacement procedures performed at the hospital during the 2-year period prior to the study, with dates comprising 9/1/2008 to 9/1/2010. Infection was diagnosed by full time surgical site infection nurses according to UK health protection agency criteria for deep surgical site infection.[16] A transition in patient warming systems from forced air to conductive fabric was made in all four orthopaedic theatres starting 3/1/2010 and ending 6/1/2010.

Statistical Analysis

A Poisson regression model was fitted to the hip replacement data having the sum of bubble counts for each experimental run (5 pictures) as the response and the two factors identified in the experimental design as predictors (including interaction). Reported values are predicted means (± standard error of the mean) for experimental factor combinations. Wald tests were used for significance ($p < 0.05$).

A logistic regression model was fitted to the joint sepsis data having infection as the response and the period (forced air, transition, and conductive fabric warming) as predictors. Reported values are predicted mean infection rates (± standard error of the mean) for each period. Wald tests were used for significance ($p < 0.05$).

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Results

Hip Replacement:

The number of bubbles reaching the surgical site measured the degree to which patient warming excess heat mobilized resident under-drape air over the anaesthesia screen and into the surgical site. Bubble counts per photograph (**Fig 4**) suggest that forced air warming generated sufficient excess heat to mobilize resident under-drape air over the anaesthesia screen. In contrast, conductive fabric warming did not generate sufficient excess heat to have the same mobilizing effect. Further, surgical drape position appeared to have a large effect on resident under-drape air mobilization into the surgical site for forced air warming, with the half-drape configuration resulting in the largest degree of resident-air mobilization.

Differences in the sum of bubble counts for each experimental run (**Fig 5**) were significant between conductive fabric and forced air warming for the drape configurations of half-drape (0 versus 68, $p<0.001$) and laid-down (0 versus 3, $p=0.010$); differences for full-drape (0 versus 1, $p=0.283$) were insignificant. It was necessary to model the sum of bubble counts for statistical inference; otherwise observations would not be independent.

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Lumbar Spinal Procedure:

Time-lapsed-photography showed forced air warming excess heat to generate hot-air convection currents that transported large quantities of floor-level resident air upwards and into the surgical site (**Fig 6**). These convection currents appeared to form in the space between the surgeon's body and the operating room table. In contrast, conductive fabric warming did not generate sufficient excess heat to establish such convection currents. Instead, with conductive fabric warming ventilation airflow patterns followed the intended path - downwards and away from the surgical site.

Joint Sepsis Rates:

A 2-year observation of deep infection in joint replacement revealed a significant reduction ($p=0.007$) in joint sepsis rates for the period conductive fabric warming was in

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clinical use versus forced air warming, with average infection rates of 0.0% (n=165) versus 3.0% (n=965), respectively (**Fig 7**). The reported *p*-value is the probability of observing 0 infections in 165 cases given a 3.0% infection rate and a binomial distribution, since model asymptotics are unstable in the region where p≈0. There was a 3-month transition period where both patient warming devices were used in the orthopaedic theatres having an infection rate of 3.7% (n=160), which was not significantly different from the infection rate of 3.0% during the forced air warming period (p=0.62). It should be noted that during this time period there were changes in the antibiotic regimen used and thromboprophylaxis protocol employed. Thus, these may be confounding factors.[17]

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Discussion

This study compared the effects of two patient warming systems, forced air and conductive fabric, on ventilation performance in an ultra-clean operating theatre during hip replacement and spinal procedures. Forced air warming excess heat was found to generate convection currents that disrupted clean-airflow patterns over the surgical site during both procedures. In contrast, conductive fabric warming released minimal excess heat and was shown to have no effect on ventilation performance in either procedure. The results also showed forced air warming excess heat to mobilize resident air from typically non-sterile areas (floor & under the anaesthesia drape) into the surgical site, a finding that may have implications regarding surgical site sterility.

Perhaps the most striking finding was the detection of hot-air convection currents originating from where the "mass-flow" of hot air exhausted the forced air warming blanket: for the hip replacement with upper-body warming, convection currents formed near the mannequin's head; for the spinal implant with lower-body warming, convection currents formed along the lower drape edge by the surgeon's legs. The formation of such convection currents may, at first, appear to be theoretically unsupported since forced air warming exhausts a heated airflow of only 40 cubic feet per minute into a ventilation environment having an airflow of 6000 cubic feet per minute.[18] However, one must also consider the effects of surgical lighting, drapes, and personnel on ventilation

performance, all of which create localized airflow disturbances that aid in convection current formation.

Prior research in ultra-clean ventilation theatres has shown surgical lighting to be a significant source of ventilation disruption through the downstream wake and associated recirculation zone.[15] In our study, the use of "bubbles" allowed us to visualize this recirculation zone, which was found to extend about 1 meter below the body of each surgical light. "Bubbles" and, thus, resident air reaching this zone tended to remain suspended in this vortex for some time. The presence of a raised anaesthesia drape was shown to further magnify the size and effect of this vortex, for the drape blocked the natural passage of air out of the ventilation field and created a "still zone" adjacent to the vortex. Lastly, the presence of a surgeon or anesthaestist near this "still zone" created an additional ventilation flow blockage[19] resulting in a situation where even the slightest movements adversely impacted the natural airflow patterns over the surgical site. Under such fragile conditions, the "mass-flow" of hot forced air warming exhaust was sufficiently buoyant to push upwards and into this locally compromised ventilation region.

The clinical concern regarding the formation of such convection currents is two-fold. First, these currents oppose the natural clean-airflow patterns that are intended to sweep contaminants down and away from the surgical site.[20] Thus, contaminants released in the vicinity of the surgical site are less likely to be cleared. Second, the upward mobilization of floor-level and under-drape air could potentially compromise the sterility of the surgical site, since resident air from these locations is typically laden with pathogens shed from the surgical staff.[21] Even small elevations in contaminant exposure could be of clinical significance given that airborne derived infection risks are exponentially magnified with implantable procedures.[22] Empirical support for the concept that observed convection currents resulted in increased surgical site contaminant exposure can be found in the observed reduction in hospital hip and knee joint replacement infection rates when a switch from forced air to conductive fabric warming was implemented. However, this infection data is observational in nature and does not

prove that such a relationship exists since we were unable to control for other measures instituted by the hospital over the 2-year period.

Further, the present study is somewhat limited in that we assessed the movements of "bubbles" as a surrogate for the movement of pathogenic contaminants. Thus, the clinical relevance of our findings depend on two assumptions: 1) that floor-level and under-drape air is non-sterile; and 2) that airborne contaminant concentrations from these locations represent a significant infection risk relative to other contamination sources. Moreover, the bulk of prior research on the risks of forced air warming has either investigated ventilation disruption due to excess heat in conventional OTs[23,24] unsuitable for orthopaedic operations or evaluated microbial contamination buildup and emission issues.[25-29] Relevant research in ultra-clean OTs is limited to a single orthopaedic study in which forced air warming resulted in elevated microbial counts over the surgical site.[30] However, the contamination increase was deemed to be far less than that resulting from personnel movements and such increases did not exceed recommended bacterial levels. Yet, it is unknown how these results translate over the range of implantable procedures performed in ultra-clean OTs. Even minor differences in factors such as surgical draping, procedural practices, and theatre dress are likely to have large effects on both floor-level and under-drape contaminant levels and the dynamics of convection current formation.

National studies on the benefits of ultra-clean ventilation may provide a better indication as to the impact of forced air warming on contaminant mobilization for they take into account the full range of surgical draping, procedural practices, and theater dress. Over the past 10 years, these studies have shown either a trend towards[31] or significantly higher[32,33] infection rates. The mobilization of non-sterile air with forced air warming may be the explanatory factor, since historical studies[1,3] on laminar flow ventilation conducted before the introduction of forced air warming showed clear infection reduction benefits.

Until the effects of forced air warming excess heat on ventilation disruption can be fully evaluated in regards to affecting the sterility of the surgical site, the use of air-free patient

warming alternatives might be recommended for implant procedures carried out in ultra-clean theatres.

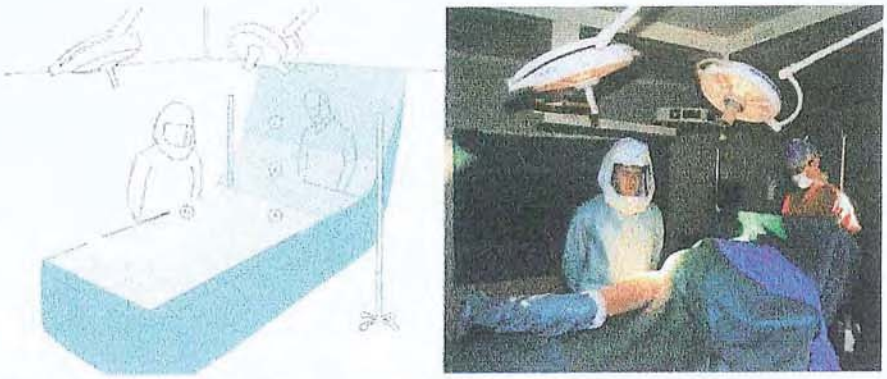

Figure 1: Hip replacement setup with upper-body warming, showing: surgical drape positions of laid-down (A), half-drape (B), and full-drape (C) and surgical site location (D)

Figure 2: Lumbar spinal setup with lower-body warming and full-drape, showing: surgical site location (A).

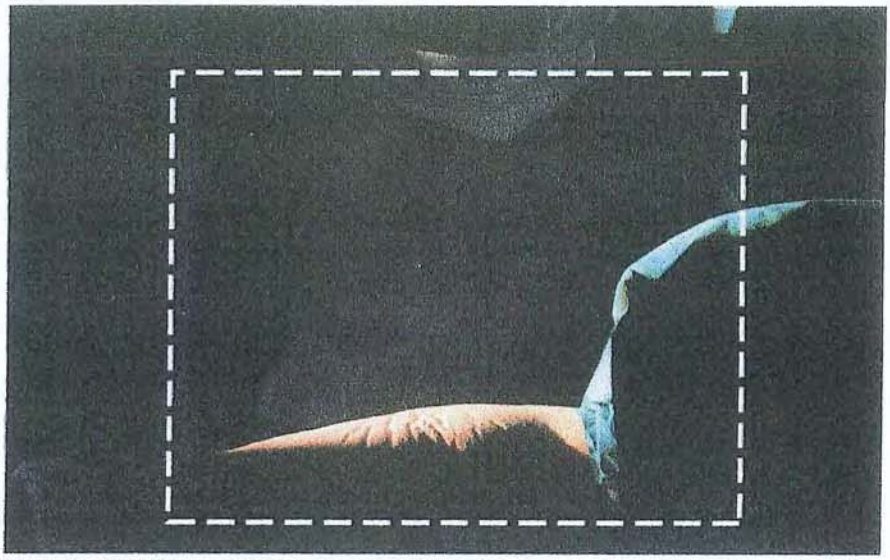

Figure 3: Definition of region where bubble counts were performed over the surgical site for hip replacement with upper-body warming. A picture shows bubbles (white steaks) appearing in the photograph for the experimental setup of forced air warming and half-drape.

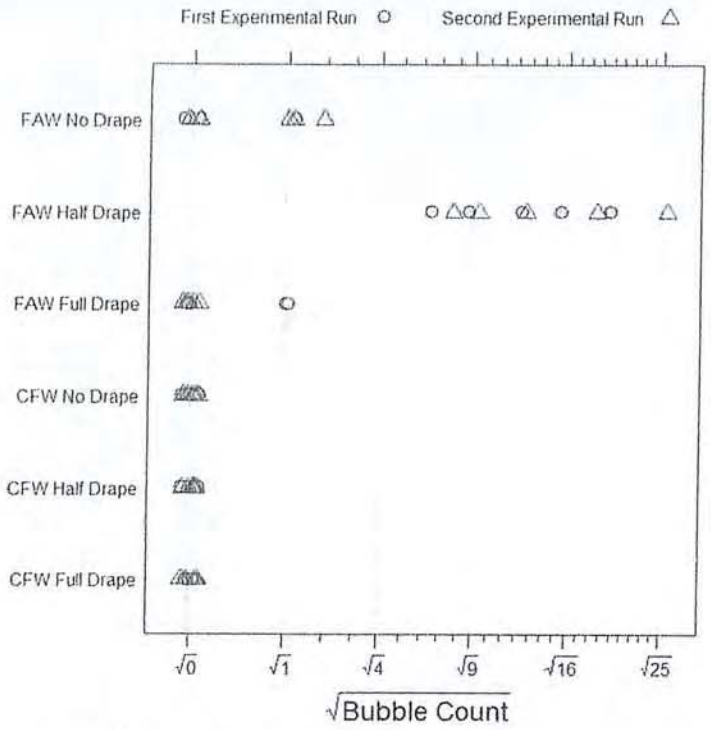

Figure 4: Bubble counts over the surgical site for each photograph (data is jittered to avoid overprinting). 5 photographs were taken for each experimental run. Abbreviations: FAW, Forced Air Warming; CFW, Conductive Fabric Warming.

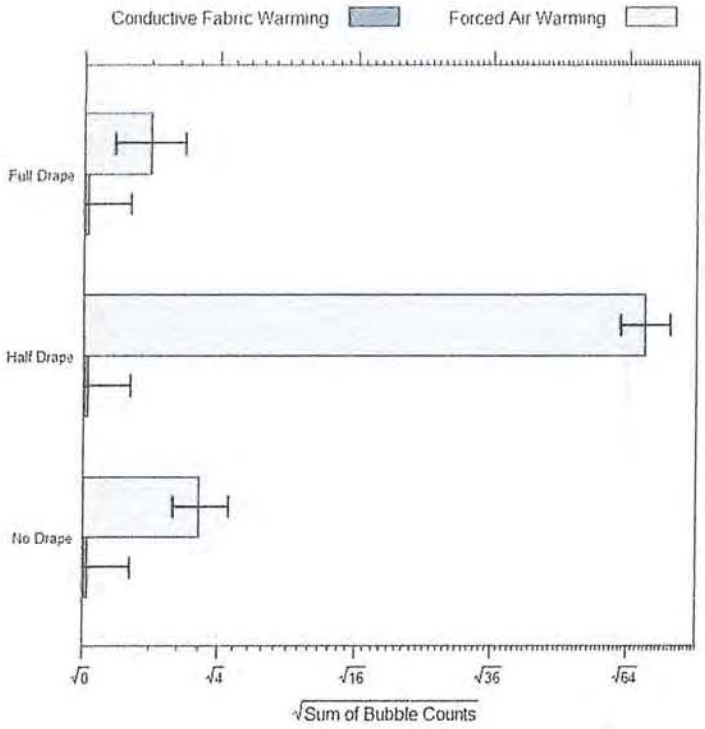

Figure 5: Average bubble count for experimental runs when the bubble counts are summed over the 5 photographs (±Standard Error of the Mean).

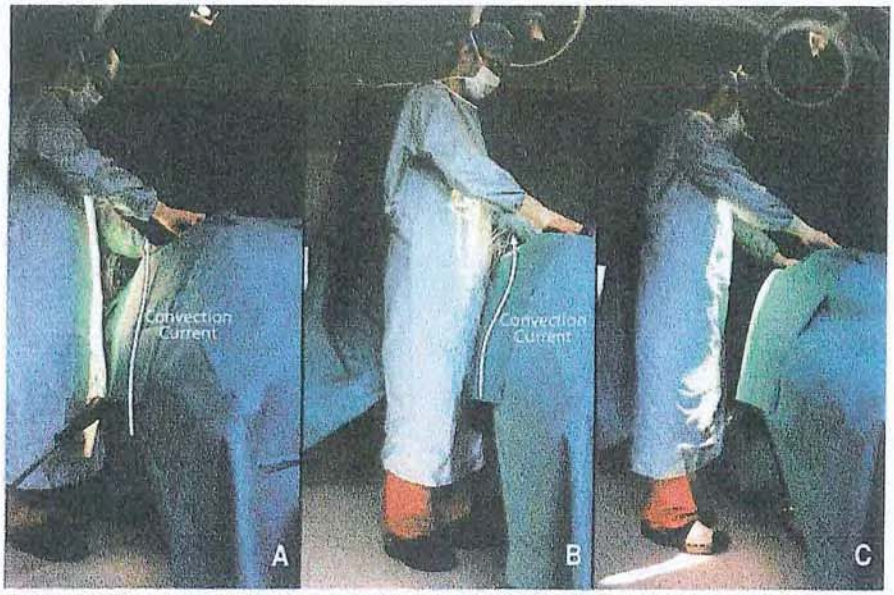

Figure 6: Time-lapsed-photography of bubbles depicting airflow patterns for lower lumbar spinal implant procedure with: (A & B) Forced air warming with resulting convection currents annotated and (C) conductive fabric warming.

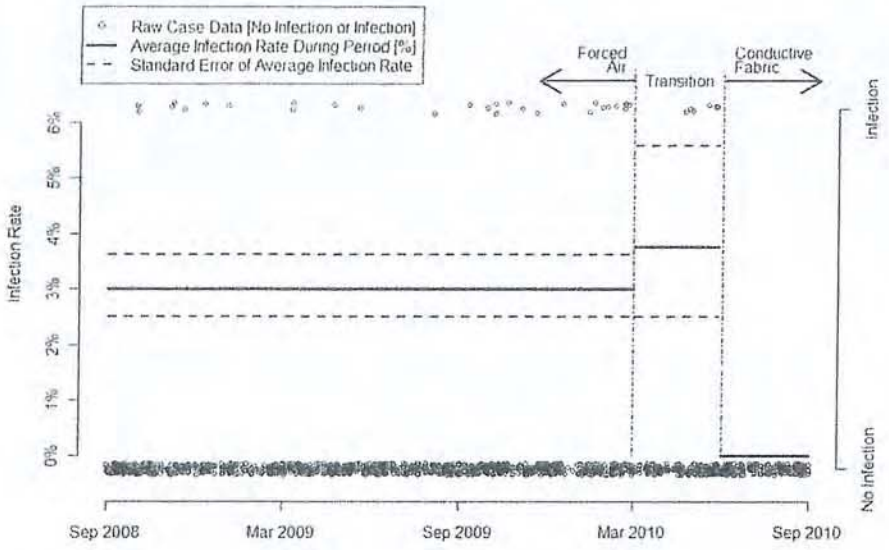

Figure 7: Infection data for n=1290 joint replacement cases with the outcome plotted on the right hand axis (data is jittered to avoid overprinting). Average infection rates for each period (Forced air, Transition, or Conductive Fabric) are plotted on the left hand axis. Standard error of the mean was estimated using logistic regression.

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Forced Air Warming and Ultra-Clean Ventilation Do Not Mix: The effect of excess vented heat on clean-airflow patterns.

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Key words: surgical site infection, forced air warming, laminar air flow, ultra clean ventilation, operating room environmental contamination, operating room ventilation, patient warming, hip replacement, knee replacement, arthroplasty.

Abstract

Introduction: Ultra-clean ventilation is designed to protect the surgical site from airborne pathogens. However, ventilation performance is fragile and depends critically on airflow volumes and temperature gradients. Patient warming systems represent a disruption risk via the excess heat they release. Therefore, we compared the effects of two patient warming systems – (1) conductive fabric and (2) forced air – on clean-airflow patterns over the surgical site during simulated hip replacement and spinal procedures.

Methods: A mannequin was draped for (1) a hip replacement and (2) a lumbar spinal implant in a partial-walled ultra-clean theatre. Neutral buoyancy detergent bubbles were released under the anaesthesia drape and at floor level to visualize air-currents and assess the mobilization of resident air into the clean-airflow over the surgical site. For the hip replacement, a randomized experimental design assessed the effects of upper-body warming system and anaesthesia drape height on bubbles reaching the surgical site. For the spinal surgery, the effect of the lower-body warming system was assessed with time-lapsed-photography of bubbles. Lastly, joint sepsis rates were tracked for a two-year period over which a change from forced air to conductive fabric was implemented.

Results: For the hip replacement, bubble counts were significantly higher for forced air than conductive fabric for laid-down (3 versus 0; p =0.010) and half-height (68 versus 0; $p < 0.001$) anaesthesia draping; differences for full-height draping were insignificant (1 versus 0; p =0.283). For the spinal surgery, time-lapsed-photography showed forced air to establish upwards convection currents that transported floor air into the surgical site; this convection current was not present with conductive fabric. Joint sepsis infection rates were reduced after the implementation of conductive fabric warming (0% for n=161) versus prior rates with forced air (3.0% for n=936).

Conclusion: Excess heat from forced air warming disrupted clean-airflow patterns over the surgical site and generated upward convection currents, which transported non-sterile air from the floor and the anaesthesia side of the drape into the surgical site; conductive fabric warming had no such effects. Observation of joint sepsis rates suggests an empirical reduction in infection with conductive fabric warming in orthopaedics.

Number of words: 339

Introduction

Although most famously remembered for pioneering the hip arthroplasty, Sir John Charnley was among the first to recognize the critical role of operating theatre (OT) ventilation in preventing joint sepsis. Charnley postulated that the "surgical implant might provide a nidus for the growth of airborne bacteria which ordinarily are accepted as non-pathogenic."[1] Research efforts confirmed Charnley's insights through animal studies[2] and a national clinical trial involving over 8000 operations demonstrating the efficacy of clean air for the reduction of arthroplasty infection rates.[3] As such, ultra-clean ventilation became the standard for orthopaedic procedures. Ultra-clean ventilation protects the surgical site from airborne contamination through the constant delivery of a downward uniform velocity (0.3 to 0.5 m/s) highly filtered (>99.997%) airflow.[4] However, the performance of ultra-clean ventilation depends critically on air-flow volumes and proper temperature gradients, the latter of which may be disrupted by excess heat released from patient warming devices.

Forced air warming is commonly used in OTs to ensure patient normothermia. The vented airflow from forced air warming is released at 43°C, which is often 20°C above ambient OT conditions.[5,6] The release of such thermal energy has the potential to establish temperature gradients that impede the downward velocity of the OT ventilation airflows. Additionally, reductions in downward flow velocity have been shown to increase contaminant entrainment into the surgical site.[7] Moreover, the release of excess heat may generate convection currents that rise against the downward airflows and mobilize non-sterile floor-level air into the surgical site.

Air-free alternatives, such as conductive fabric warming, have been developed that are comparably effective to forced air for the prevention of surgical hypothermia.[8-14] These alternatives have much higher thermal efficiencies than forced air warming and, therefore, release only a fraction of the excess heat.[6] As such, there is a need to critically assess the impact of forced air warming versus air-free alternatives on ultra-clean ventilation performance. Specifically, we compared the effects of (1) conductive fabric and (2) forced air warming on clean-airflow patterns over the surgical site in a partial-

walled ultra-clean OT during two procedures representing the variety of implantable operations typically encountered: 1) a hip replacement with upper-body warming, and 2) a lumbar spinal surgery with lower-body warming. Ventilation airflow patterns were visualized using neutrally buoyant detergent bubbles and observational data on joint sepsis rates were compared for the period each warming device was in clinical use.

Methods

Ultra-Clean Operating Theatre Characteristics:

Experiments were carried out in a partial-walled ultra-clean OT (ExFlow 90, Howorth, United Kingdom) used for orthopaedic and spinal surgery in the United Kingdom. Validation and verification checks per HTM 2025 showed the OT airflows to be within specification and having a mean velocity of 0.44 m/s two-meters off the floor, which is above the threshold required by the standards (0.38 m/s). However, an insignificant airflow imbalance was detected during validation testing due to the location of the theatre prep room that affected the results of a single particle entrainment test; entrainment values were 12% at that location, which marginally exceeded the recommended threshold of 10%. This marginal discrepancy was unlikely to have any effect on the results of the study because smoke testing detected normal airflow patterns under the canopy and the OT passed microbial contamination testing.

Airflow Visualization Procedures:

High intensity lighting was used to illuminate neutrally buoyant detergent bubbles having a 4 mm average diameter (referred to herein as "bubbles"). "Bubbles" were produced by a bubble generator (Sage Action, Ithaca, NY), which utilized a helium-mixed air supply, detergent, and centripetal bubble size classification filter. The bubble generator is specifically designed and validated for the visualization of air currents.[15] For photography, a digital camera (500D, Canon, Surrey, UK) was employed and shutter exposure time was set to ¼ of a second for time-lapsed-photography.

Experimental Setup: Hip Replacement

A mannequin was laid in the lateral position on an operating table and draped with a 3-piece orthopaedic kit (Molnlycke Health Care, Manchester, UK) in accordance with standard protocols (**Fig 1**). A surgeon, dressed in occlusive clothing with head gear (T4, Stryker, Kalamazoo, MI), and an anaesthesiologist stood motionless in front of the surgical site and behind the anaesthesia screen. At the head of the operating table, the surgical drape was either: 1) clipped to the ceiling to create a barrier between the surgical site and anaesthesia area (full-drape); 2) clipped to IV poles and raised 0.75 meters above

the operating table (half-drape); or 3) laid-down over the mannequin's head (laid-down). The experimental upper-body warming treatment was introduced under the drape and was either: 1) a torso forced air blanket (Bair Hugger Model 540, Arizant Healthcare, Eden Prairie, MN); or 2) a torso conductive fabric blanket (Hot Dog Model B110, Augustine Temperature Management, Eden Prairie, MN). The blankets were powered by standard controllers set to 43°C (conductive fabric - Model WC02, Augustine Temperature Management; forced air - Model 750, Arizant Healthcare). "Bubbles" were introduced at the neck of the mannequin to track under-drape resident air movements in the region where the excess patient warming heat was being released.

Experimental Setup: Lumbar Spinal Procedure

The same mannequin was laid in the prone position on the operating table and four drapes were arranged in a "square" configuration (Molnlycke Health Care) with the anaesthesia screen at full-height in accordance with standard protocols (**Fig 2**). A single surgeon stood motionless next to the surgical site for all experiments. The experimental lower-body warming treatment was introduced under the drape and was either: 1) a lower-body forced air blanket (Bair Hugger Model 525, Arizant Healthcare); or 2) a lower-body conductive fabric blanket (Hot Dog Model B103, Augustine Temperature Management). The blankets were powered by the same controllers as listed above set to 43°C. "Bubbles" were introduced at floor level between the surgeon's body and the operating room table in the region where the patient warming excess heat was being released.

Sampling Procedures

Hip Replacement: Bubble counts over the surgical site were measured for each experimental treatment using a sequence of five photographs taken at ten-second intervals. The number of bubbles reaching the surgical site was determined by counting the number of bubbles in a 0.5 by 0.5 meter region over the surgical site in each photograph (**Fig 3**).

Lumbar Spinal Procedure: Time-lapsed-photography was chosen over the use of bubble counts to show differences in ventilation performance between patient warming systems given the significant change in observed surgical site airflow patterns (see **Results**).

Experimental Design

Hip Arthroplasty: A replicated (n=2) $3^1 2^1$ full factorial design was employed to assess changes in bubble counts over the surgical site. The experimental factors considered were: 1) anaesthesia screen: laid-down, half-screen, or full-screen; and 2) patient warming device: conductive fabric or forced air.

Lumbar Spinal Procedure: No design was employed or necessary to demonstrate the difference in ventilation performance between forced air and conductive fabric patient warming systems (see **Results**).

Joint Sepsis Data

Joint sepsis data was collected for primary hip and knee replacement procedures performed at the hospital during the 2.5-year period prior to the study, with dates comprising 7/1/2008 to 1/1/2011. Infection was diagnosed by full time surgical site infection nurses according to UK health protection agency criteria for deep surgical site infection.[16] A transition in patient warming systems from forced air to conductive fabric was made in all four orthopaedic theatres starting 3/1/2010 and ending 6/1/2010.

Statistical Analysis

A Poisson regression model was fitted to the hip replacement data having the sum of bubble counts for each experimental run (5 pictures) as the response and the two factors identified in the experimental design as predictors (including interaction). Reported values are predicted means (± standard error of the mean) for experimental factor combinations.

A logistic regression model was fitted to the joint sepsis data having infection as the response and the period (forced air, transition, and conductive fabric warming) as predictors. Reported values are predicted mean infection rates (± standard error of the mean) for each period.

For both models, Wald tests were conducted at the $\alpha = 0.05$ level of statistical significance .

Results

Hip Replacement:

The number of bubbles reaching the surgical site measured the degree to which patient warming excess heat mobilized resident under-drape air over the anaesthesia screen and into the surgical site. Bubble counts per photograph (**Fig 4**) suggest that forced air warming generated sufficient excess heat to mobilize resident under-drape air over the anaesthesia screen. In contrast, conductive fabric warming did not generate sufficient excess heat to have the same mobilizing effect. Further, surgical drape position appeared to have a large effect on resident under-drape air mobilization into the surgical site for forced air warming, with the half-drape configuration resulting in the largest degree of resident-air mobilization.

Differences in the sum of bubble counts for each experimental run (**Fig 5**) were significant between conductive fabric and forced air warming for the drape configurations of half-drape (0 versus 68, $p<0.001$) and laid-down (0 versus 3, $p=0.010$); differences for full-drape (0 versus 1, $p=0.283$) were insignificant. It was necessary to model the sum of bubble counts for statistical inference; otherwise observations would not be independent.

Lumbar Spinal Procedure:

Time-lapsed-photography showed that excess heat from forced air warming generated hot-air convection currents that transported large quantities of floor-level resident air upwards and into the surgical site (**Fig 6**). These convection currents appeared to form in the space between the surgeon's body and the operating room table. In contrast, conductive fabric warming did not generate sufficient excess heat to establish such convection currents. Instead, with conductive fabric warming ventilation airflow patterns followed the intended path - downwards and away from the surgical site.

Joint Sepsis Rates:

A 2.5-year observational study of deep infection in joint replacement revealed a significant reduction ($p=0.043$) in joint sepsis rates for the period conductive fabric

warming was in clinical use versus forced air warming, with average infection rates of 1.08% (n=372) versus 3.10% (n=1065), respectively (**Fig 7**). There was a 3-month transition period where both patient warming devices were used in the orthopaedic theatres having an infection rate of 3.75% (n=160), which was not significantly different from the infection rate of 3.0% during the forced air warming period (p=0.662). It should be noted that during this time period there were changes in the antibiotic regimen used and thromboprophylaxis protocol employed.[17] Thus, these may be confounding factors.

Discussion

This study compared the effects of two patient warming systems, forced air and conductive fabric, on ventilation performance in an ultra-clean operating theatre during hip replacement and spinal procedures. Forced air warming excess heat was found to generate convection currents that disrupted clean-airflow patterns over the surgical site during both procedures. In contrast, conductive fabric warming released minimal excess heat and was shown to have no effect on ventilation performance in either procedure. The results also showed forced air warming excess heat to mobilize resident air from typically non-sterile areas (floor & under the anaesthesia drape) into the surgical site, a finding that may have implications regarding surgical site sterility.

Perhaps the most striking finding was the detection of hot-air convection currents originating from where the "mass-flow" of hot air exhausted the forced air warming blanket: for the hip replacement with upper-body warming, convection currents formed near the mannequin's head; for the spinal implant with lower-body warming, convection currents formed along the lower drape edge by the surgeon's legs. The formation of such convection currents may, at first, appear to be theoretically unsupported since forced air warming exhausts a heated airflow of only 40 cubic feet per minute into a ventilation environment having an airflow of 6000 cubic feet per minute.[18] However, one must also consider the effects of surgical lighting, drapes, and personnel on ventilation performance, all of which create localized airflow disturbances that aid in convection current formation.

Prior research in ultra-clean ventilation theatres has shown surgical lighting to be a significant source of ventilation disruption through the downstream wake and associated recirculation zone.[15] In our study, the use of "bubbles" allowed us to visualize this recirculation zone, which was found to extend about 1 meter below the body of each surgical light. "Bubbles" and, thus, resident air reaching this zone tended to remain suspended in this vortex for some time. The presence of a raised anaesthesia drape was shown to further magnify the size and effect of this vortex, for the drape blocked the natural passage of air out of the ventilation field and created a "still zone" adjacent to the vortex. Lastly, the presence of a surgeon or anaesthetist near this "still zone" created an additional ventilation flow blockage[19] resulting in a situation where even the slightest movements adversely impacted the natural airflow patterns over the surgical site. Under such fragile conditions, the "mass-flow" of hot forced air warming exhaust was sufficiently buoyant to push upwards and into this locally compromised ventilation region.

The clinical concern regarding the formation of such convection currents is two-fold. First, these currents oppose the natural clean-airflow patterns that are intended to sweep contaminants down and away from the surgical site.[20] Thus, contaminants released in the vicinity of the surgical site are less likely to be cleared. Second, the upward mobilization of floor-level and under-drape air could potentially compromise the sterility of the surgical site, since resident air from these locations is typically laden with pathogens shed from the surgical staff.[21] Even small elevations in contaminant exposure could be of clinical significance given that airborne derived infection risks are exponentially magnified with implantable procedures.[22] Empirical support for the concept that observed convection currents resulted in increased surgical site contaminant exposure can be found in the observed reduction in hospital hip and knee joint replacement infection rates when a switch from forced air to conductive fabric warming was implemented. However, this infection data is observational in nature and does not prove that such a relationship exists since we were unable to control for other measures instituted by the hospital over the 2-year period.

Further, the present study is somewhat limited in that we assessed the movements of "bubbles" as a surrogate for the movement of pathogenic contaminants. Thus, the clinical relevance of our findings depend on two assumptions: 1) that floor-level and under-drape air is non-sterile; and 2) that airborne contaminant concentrations from these locations represent a significant infection risk relative to other contamination sources. Moreover, the bulk of prior research on the risks of forced air warming has either investigated ventilation disruption due to excess heat in conventional OTs[23,24] unsuitable for orthopaedic operations or evaluated microbial contamination buildup and emission issues.[25-29] Relevant research in ultra-clean OTs is limited to a single orthopaedic study in which forced air warming resulted in elevated microbial counts over the surgical site.[30] However, the contamination increase was deemed to be far less than that resulting from personnel movements and such increases did not exceed recommended bacterial levels. Yet, it is unknown how these results translate over the range of implantable procedures performed in ultra-clean OTs. Even minor differences in factors such as surgical draping, procedural practices, and theatre dress are likely to have large effects on both floor-level and under-drape contaminant levels and the dynamics of convection current formation.

National studies on the benefits of ultra-clean ventilation may provide a better indication as to the impact of forced air warming on contaminant mobilization for they take into account the full range of surgical draping, procedural practices, and theater dress. Over the past 10 years, these studies have shown either a trend towards[31] or significantly higher[32,33] infection rates. The mobilization of non-sterile air with forced air warming may be the explanatory factor, since historical studies[1,3] on laminar flow ventilation conducted before the introduction of forced air warming showed clear infection reduction benefits.

Until the effects of forced air warming excess heat on ventilation disruption can be fully evaluated in regards to affecting the sterility of the surgical site, the use of air-free patient warming alternatives might be recommended for implant procedures carried out in ultra-clean theatres.

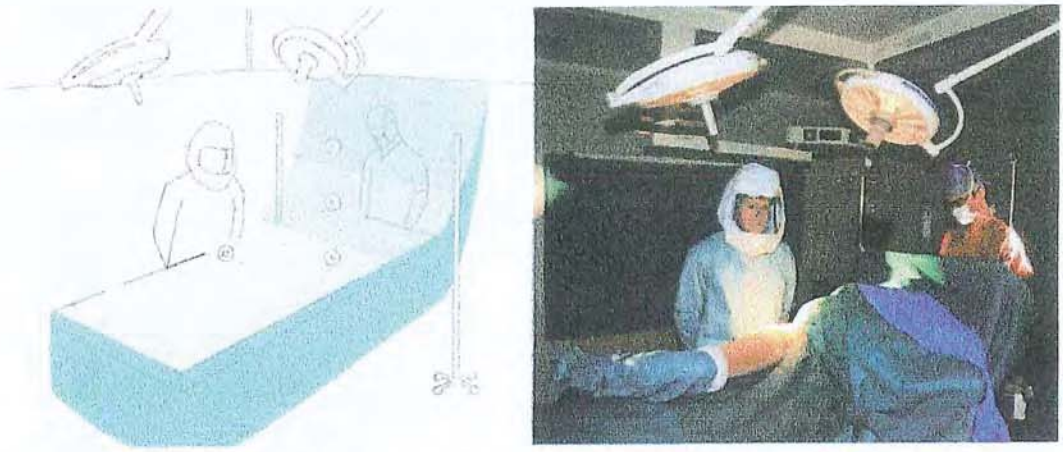

Figure 1: Hip replacement setup with upper-body warming, showing: surgical drape positions of laid-down (A), half-drape (B), and full-drape (C) and surgical site location (D)

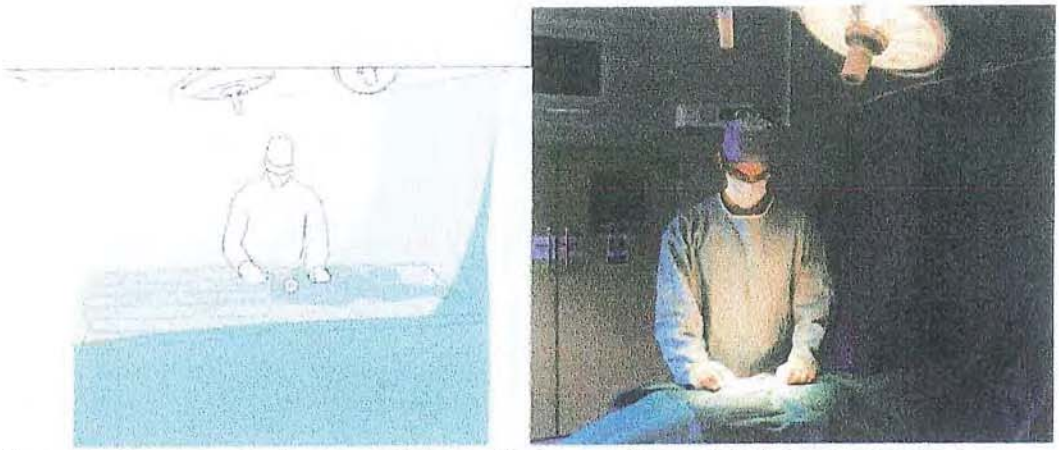

Figure 2: Lumbar spinal setup with lower-body warming and full-drape, showing: surgical site location (A).

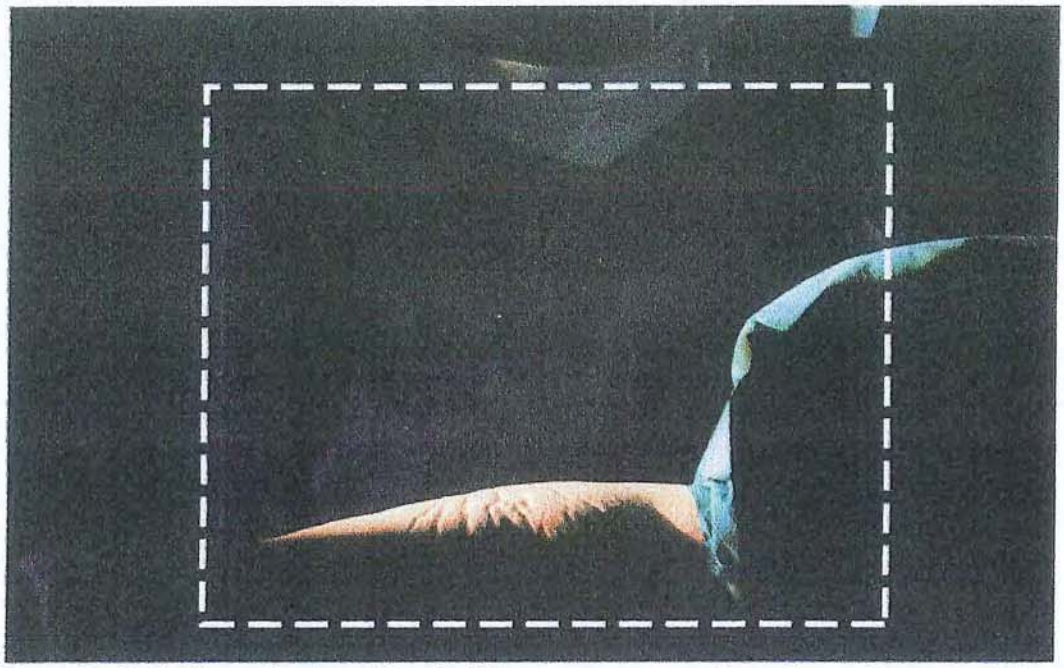

Figure 3: Definition of region where bubble counts were performed over the surgical site for hip replacement with upper-body warming. A picture shows bubbles (white steaks) appearing in the photograph for the experimental setup of forced air warming and half-drape.

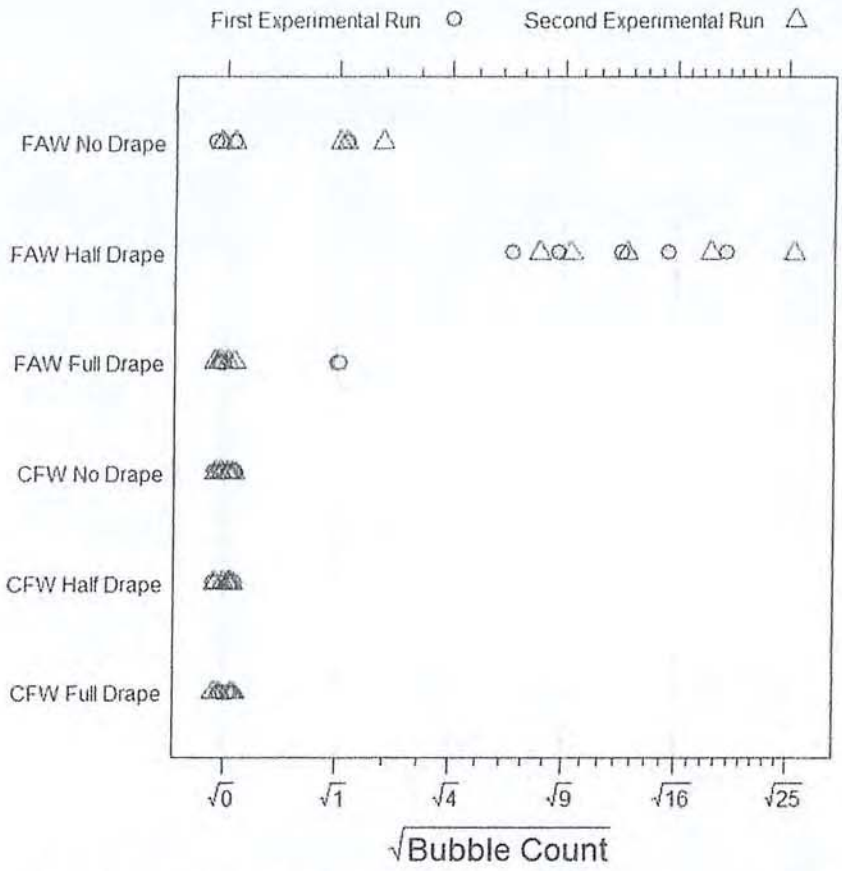

Figure 4: Bubble counts over the surgical site for each photograph (data is jittered to avoid overprinting). 5 photographs were taken for each experimental run. Abbreviations: FAW, Forced Air Warming; CFW, Conductive Fabric Warming.

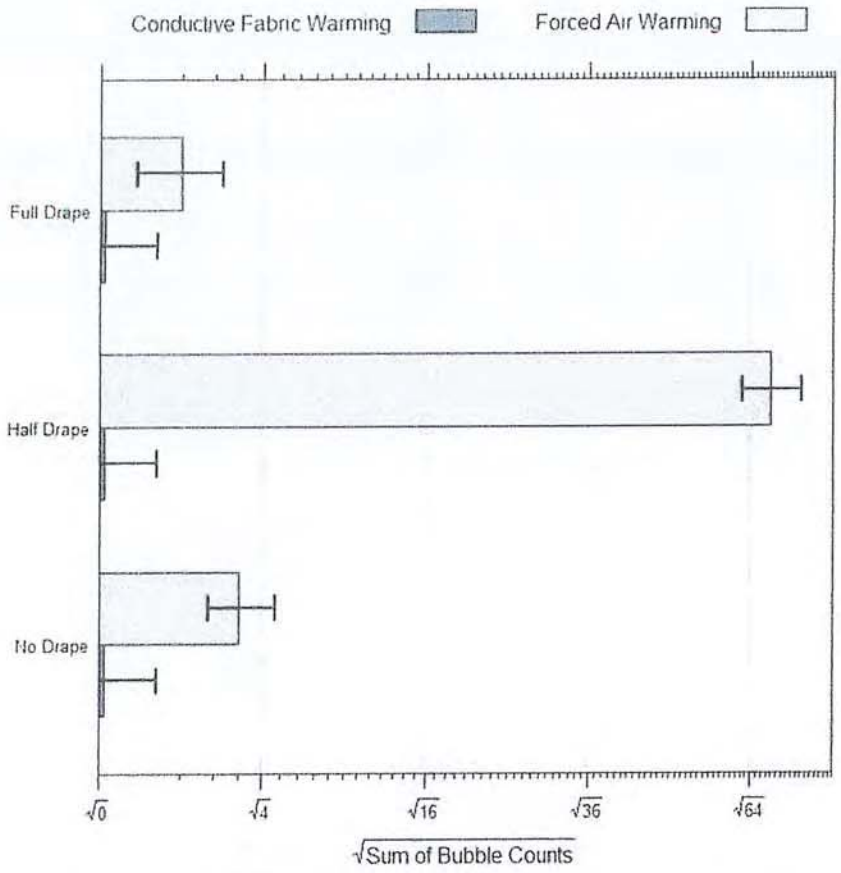

Figure 5: Average bubble count for experimental runs when the bubble counts are summed over the 5 photographs (±Standard Error of the Mean).

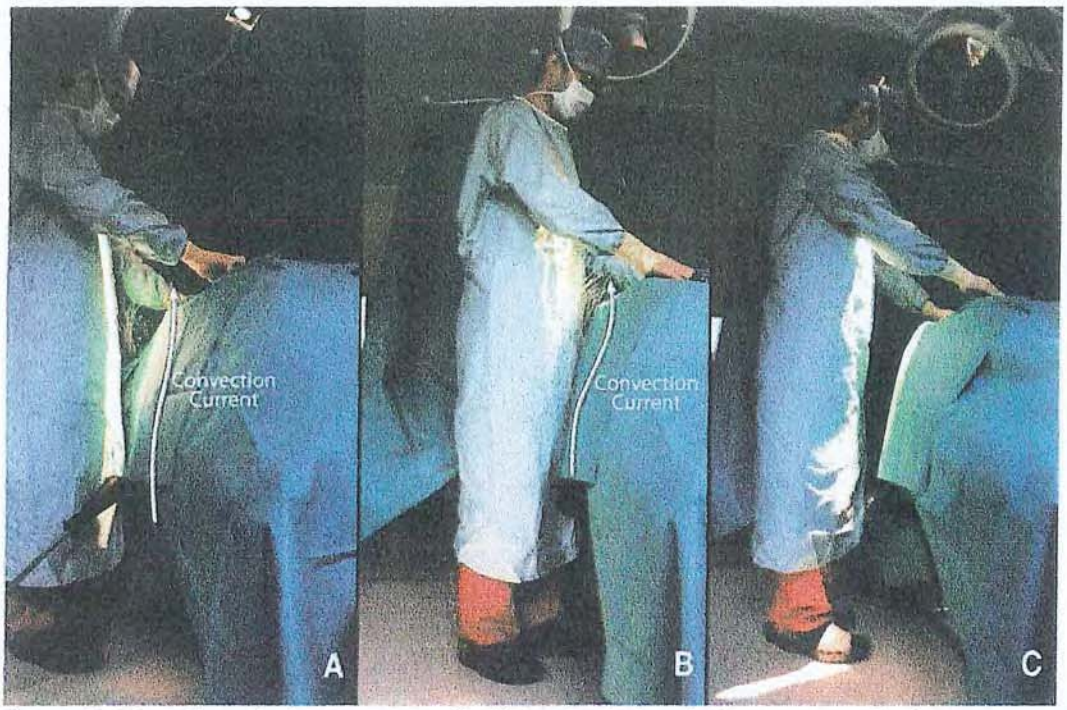

Figure 6: Time-lapsed-photography of bubbles depicting airflow patterns for lower lumbar spinal implant procedure with: (A & B) Forced air warming with resulting convection currents annotated and (C) conductive fabric warming.

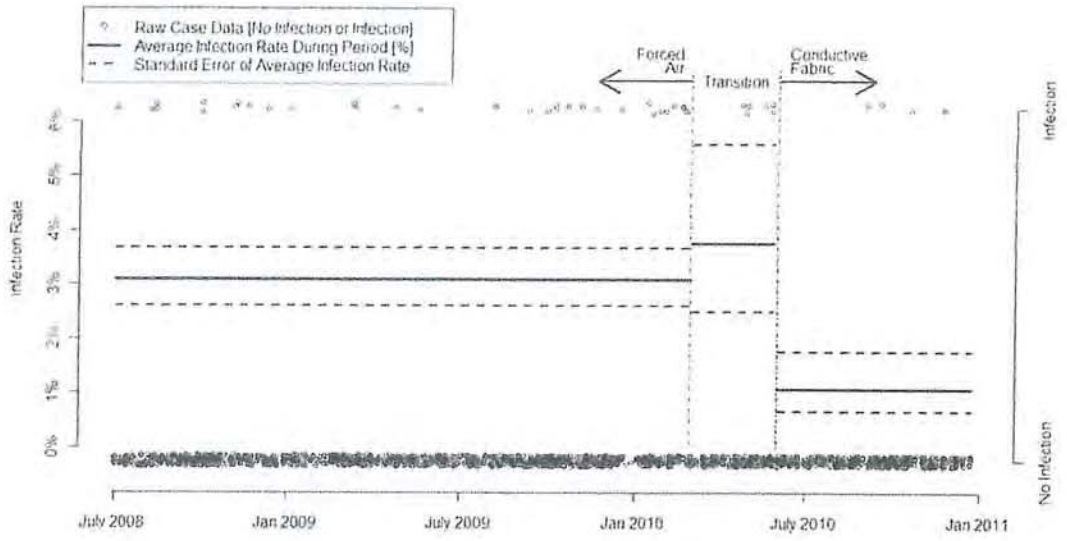

Figure 7: Infection data for n=1597 joint replacement cases with the outcome plotted on the right hand axis (data is jittered to avoid overprinting). Average infection rates for each period (Forced air, Transition, or Conductive Fabric) are plotted on the left hand axis. Standard error for the average infection rate was estimated using logistic regression.

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EXHIBIT DX26

TO DECLARATION OF COREY L. GORDON IN SUPPORT OF DEFENDANTS' OPPOSITION TO PLAINTIFFS' MOTIONS TO EXCLUDE TESTIMONY OF THEODORE HOLFORD AND JONATHAN BORAK

Christopher Nachtsheim <nacht001@umn.edu>

British Hip Society presentation

11 messages

Paul McGovern <pdmcgovern@gmail.com> Wed, Feb 16, 2011 at 1:50 PM
To: malbrecht@augbiomed.com, Mike Reed Cons Wansbeck <mike.reed@nhs.net>
Cc: Scott Augustine <saugustine@augbiomed.com>, Brent Augustine <baugustine@augbiomed.com>, nacht001@umn.edu

Mark,

Sorry I've been quiet, had quite a few deadlines. Have had a quick look at the writeup, looks great, will review and get back to you this week

I have attached an outline script for the BHS presentation, image placeholders on left, script on right...notes and queries in yellow - comments gratefully received...
Mike, is it best to leave some stuff for the discussion or get everything out in the main body?

I wonder if it needs more on results/discussion. I think the videos will produce a good effect in the room.

Anyone coming to this in addition to Mike and myself out of interest?

cheers
Paul

--
Paul McGovern

Outline of BHS presentation.docx
835K

Mark Albrecht <malbrecht@augbiomed.com> Wed, Feb 16, 2011 at 4:50 PM
To: Paul McGovern <pdmcgovern@gmail.com>, Mike Reed Cons Wansbeck <mike.reed@nhs.net>
Cc: Scott Augustine <saugustine@augbiomed.com>, Brent Augustine <baugustine@augbiomed.com>, nacht001@umn.edu

Paul,

I will certainly review this tomorrow morning first thing.

Thanks

-mark

From: Paul McGovern [mailto:pdmcgovern@gmail.com]

Sent: Wednesday, February 16, 2011 1:51 PM
To: malbrecht@augbiomed.com; Mike Reed Cons Wansbeck
Cc: Scott Augustine; Brent Augustine; nacht001@umn.edu
Subject: British Hip Society presentation

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Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH) <mike.reed@nhs.net> Wed, Feb 16, 2011 at 4:58 PM
To: Paul McGovern <pdmcgovern@gmail.com>, "malbrecht@augbiomed.com" <malbrecht@augbiomed.com>
Cc: Scott Augustine <saugustine@augbiomed.com>, Brent Augustine <baugustine@augbiomed.com>, "nacht001@umn.edu" <nacht001@umn.edu>

Comments attached. Paul – are you very clear how to save videos within ppt. Don't want any upsets on the day!

Mike

From: Paul McGovern [mailto:pdmcgovern@gmail.com]
Sent: 16 February 2011 19:51
To: malbrecht@augbiomed.com; Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH)
Cc: Scott Augustine; Brent Augustine; nacht001@umn.edu
Subject: British Hip Society presentation

Mark,

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Mark Albrecht <malbrecht@augbiomed.com> Thu, Feb 17, 2011 at 12:07 PM
To: "Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH)" <mike.reed@nhs.net>, Paul McGovern <pdmcgovern@gmail.com>
Cc: Scott Augustine <saugustine@augbiomed.com>, Brent Augustine <baugustine@augbiomed.com>, nacht001@umn.edu

Paul and Mike,

I've included some suggestions. I might also suggest shortening this a bit, it looks too long for a 10 minute spot right now. Little too heavy on the background info I think. I'll get you the product picture and infection data chart

-Mark

From: Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH) [mailto:mike.reed@nhs.net]
Sent: Wednesday, February 16, 2011 4:59 PM
To: Paul McGovern; malbrecht@augbiomed.com
Cc: Scott Augustine; Brent Augustine; nacht001@umn.edu
Subject: RE: British Hip Society presentation

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Outline of BHS presentation FAW vv CFW.doc
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Mark Albrecht <malbrecht@augbiomed.com> Thu, Feb 17, 2011 at 1:33 PM
To: "Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH)" <mike.reed@nhs.net>, Paul McGovern <pdmcgovern@gmail.com>
Cc: Scott Augustine <saugustine@augbiomed.com>, Brent Augustine <baugustine@augbiomed.com>, nacht001@umn.edu

Graph attached and r-code for it.

References in order presented on the chart are:

1. Lidwell OM. Clean air at operation and subsequent sepsis in the joint. Clin. Orthop. Relat. Res. 1986 Oct;(211):91-102.

2. Lidwell OM, Elson RA, Lowbury EJ, Whyte W, Blowers R, Stanley SJ, et al. Ultraclean air and antibiotics for prevention of postoperative infection. A multicenter study of 8,052 joint replacement operations. Acta Orthop Scand. 1987 Feb;58(1):4-13.

3. Brandt C, Hott U, Sohr D, Daschner F, Gastmeier P, Rüden H. Operating room ventilation with laminar airflow shows no protective effect on the surgical site infection rate in orthopedic and abdominal surgery. Ann. Surg. 2008 Nov;248(5):695-700.

4. Hooper GJ, Rothwell AG, Frampton C, Wyatt MC. Does the use of laminar flow and space suits reduce early deep infection after total hip and knee replacement?: THE TEN-YEAR RESULTS OF THE NEW ZEALAND JOINT REGISTRY. J Bone Joint Surg Br. 2011 Jan;93(1):85-90.

From: Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH) [mailto:mike.reed@nhs.net]
Sent: Wednesday, February 16, 2011 4:59 PM
To: Paul McGovern; malbrecht@augbiomed.com
Cc: Scott Augustine; Brent Augustine; nacht001@umn.edu
Subject: RE: British Hip Society presentation

Comments attached. Paul – are you very clear how to save videos within ppt. Don't want any upsets on the day!

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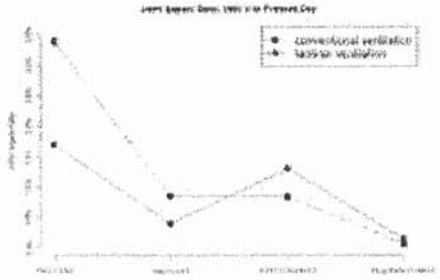
2 attachments



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paul_graph.r
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Paul McGovern <pdmcgovern@gmail.com> Sat, Feb 19, 2011 at 7:37 AM
To: Mark Albrecht <malbrecht@augbiomed.com>
Cc: "Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH)" <mike.reed@nhs.net>, Scott Augustine <saugustine@augbiomed.com>, Brent Augustine <baugustine@augbiomed.com>, nacht001@umn.edu

Next version of presentation. Have re-jigged the order a bit. It's too long but I have that under control, I will tighten the language after the content.

Cheers

Paul
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--
Paul McGovern

Outline of BHS presentation PDM version 2.docx
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Mark Albrecht <malbrecht@augbiomed.com> Mon, Feb 21, 2011 at 9:27 AM
To: Paul McGovern <pdmcgovern@gmail.com>
Cc: "Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH)" <mike.reed@nhs.net>, Scott Augustine <saugustine@augbiomed.com>, Brent Augustine <baugustine@augbiomed.com>, nacht001@umn.edu

Much better Paul,

You did a good job of hiding the "agenda" and making this look much more impartial. I'll give you an updated infection graph and summary tomorrow.

-Mark

From: Paul McGovern [mailto:pdmcgovern@gmail.com]
Sent: Saturday, February 19, 2011 7:38 AM
To: Mark Albrecht
Cc: Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH); Scott Augustine; Brent Augustine; nacht001@umn.edu
Subject: Re: British Hip Society presentation

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Brent Augustine <baugustine@augbiomed.com> Tue, Feb 22, 2011 at 12:55 PM
To: Mark <malbrecht@augbiomed.com>, Paul McGovern <pdmcgovern@gmail.com>
Cc: "Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH)" <mike.reed@nhs.net>, Scott Augustine <saugustine@augbiomed.com>, nacht001@umn.edu

I think it looks great. Mark and Paul, do you guys still need some images from me? I still have a short list of graphics that we penciled into the PowerPoint that haven't been finished. Let me know. Dr. Reed, it was nice to see you in San Diego, the research was extremely well received by those that saw it. As one Orthopod said,

"It's nice to see people doing research on practical things that have a big impact on patient outcomes."

Brent
[Quoted text hidden]
[Quoted text hidden]

Mark Albrecht <malbrecht@augbiomed.com> Tue, Feb 22, 2011 at 12:58 PM
To: Brent Augustine <baugustine@augbiomed.com>, Paul McGovern <pdmcgovern@gmail.com>
Cc: "Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH)" <mike.reed@nhs.net>, Scott Augustine <saugustine@augbiomed.com>, nacht001@umn.edu

Brent,

I'm putting together the poster today and I'll need a little help in a couple of areas. I'll come see you when I get the draft pics together.

Thanks

-Mark

From: Brent Augustine [mailto:baugustine@augbiomed.com]
Sent: Tuesday, February 22, 2011 12:55 PM
To: Mark; 'Paul McGovern'
Cc: 'Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH)'; Scott Augustine; nacht001@umn.edu

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Paul McGovern <pdmcgovern@gmail.com> Tue, Feb 22, 2011 at 1:10 PM
To: Mark Albrecht <malbrecht@augbiomed.com>
Cc: Brent Augustine <baugustine@augbiomed.com>, "Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH)" <mike.reed@nhs.net>, Scott Augustine <saugustine@augbiomed.com>, nacht001@umn.edu

Hi Brent,

Would it be possible to alter that animation of the operation setup so the uppermost leg is outside the drape, as per the photo in the subsequent slide? It's not a big problem if it's not there as I could explain it, but someone might pick up on it. If it's easier it would be fine to have the animation frames as separate images, I could then sequence them and transition them in the slideshow. Either way is fine for me.

I personally don't need any more images for the presentation, unless you would prefer a different bair hugger pic, I was going to use one of the following rather than the image of the blower unit

http://www.puls-norge.no/ImageVault/Images/id_19278/scope_128/webSafe_1/ImageVaultHandler.aspx?~19278~
http://www.puls-norge.no/ImageVault/Images/id_19110/scope_128/webSafe_1/ImageVaultHandler.aspx?~19110~

but if there is one that's more appropriate I can use that instead.

cheers
Paul

[Quoted text hidden]
--
Paul McGovern

Mark Albrecht <malbrecht@augbiomed.com> Tue, Feb 22, 2011 at 3:26 PM
To: Paul McGovern <pdmcgovern@gmail.com>
Cc: Brent Augustine <baugustine@augbiomed.com>, "Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH)" <mike.reed@nhs.net>, Scott Augustine <saugustine@augbiomed.com>, nacht001@umn.edu

Guys,

Here is a rough outline of the poster to let you know that I'm working on it. I'm making the graphs as we speak. Should be done in reasonably short order.

-m

From: Paul McGovern [mailto:pdmcgovern@gmail.com]
Sent: Tuesday, February 22, 2011 1:10 PM
To: Mark Albrecht
Cc: Brent Augustine; Reed Mike (NORTHUMBRIA HEALTHCARE NHS FOUNDATION TRUST - NE29 8NH); Scott Augustine; nacht001@umn.edu

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EXHIBIT DX27

TO DECLARATION OF COREY L. GORDON IN SUPPORT OF DEFENDANTS' OPPOSITION TO PLAINTIFFS' MOTIONS TO EXCLUDE TESTIMONY OF THEODORE HOLFORD AND JONATHAN BORAK

Outline of BHS presentation

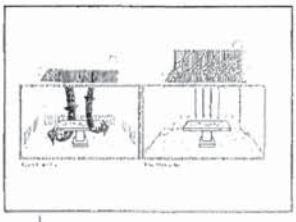
Intro/title slide

Introduce self

- Paul McGovern, ortho reg etc.
- Senior author Mike Reed, ortho consultant etc.
- Study Conducted at Wansbeck Hospital in Northumberland in 2010

Background to study

This study investigated the effect forced air warming blankets have on laminar flow in an operating theatre



Laminar Flow

Laminar flow is commonly employed in orthopaedic operating theatres with the specific aim of reducing infection rates by minimising contamination of the operative field by airborne pathogens

~~[Quote study demonstrating reduction in infection rates (need references)]~~

Why Has Laminar Ventilation Failed us?

-Go through the infection trends over the last 50 years highlighting the failure, as of late, to provide infection reduction benefits.

[Quote 4 studies demonstrating reduction in infection rates (need references)]

~~Laminar flow theatres vary in design and specification, but generally employ a HEPA filter and a laminar flow system capable of providing a consistent downward stream of highly filtered air in the area of surgery~~

What might be responsible?

-changes in infection reporting
-changes in surgical practices
-rise in drug resistant pathogens
-Lastly, the adoption of forced air warming

Patient Warming

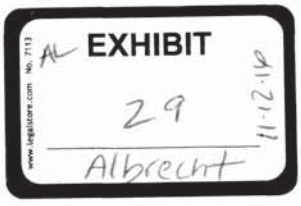
Benefits of warming slide

Comment [MRR1]: Mark has a great side that he made that shows how the effect of laminar flow has changed over the last few years – starting with Charnley. If the recent NZ registry paper could be added to that slide (please Mark) then that is a great intro to the topic.

Comment [m2]: I agree with mike, I'll give you the updated graph. Really, the question is "Why has laminar flow failed us as of late?" We must try to investigate this question.

Formatted: Font: Italic

Comment [m3]: I suggest you add this as an additional slide to focus the direction of where you are going in the broader context, that you are only looking at one potential factor among may possible culprits. This makes it look impartial and hides our agenda, so to speak...



Intraoperative patient warming significantly improves patient outcomes [reference]

Comment [m4]: Drop this slide, I'd suggest moving this information down to your ? mark slide and use a compound statement to introduce the idea, something like: Forced air warming has many established clinical beneifts such as XX, and YY... However, the heated airflow presents a ventilation disruption risk....
Therefore, we evaluated...

As it stands, this slide is simply stating facts and not making an argument. To capture attention, an argument must be carried forward in every slide. We think this because X and Y etc...

Forced air warming is the most commonly used intraoperative patient warming technique. The patient is covered with a specifically designed semiporous blanket, which is attached by an air hose to a blower unit. This blows heated air over the patient to produce the warming effect

Comment [MRR5]: Is the picture the same model as the one we used?

? slide

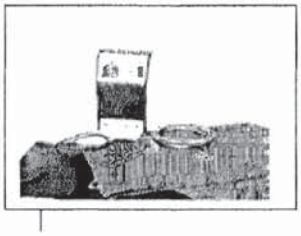
Our clinical concern was that there was a potential for hot rising air from the forced air system to disrupt laminar airflow, with possible consequences for airborne pathogenic contamination.

Our study evaluated the effect forced air warming has on laminar airflow in a simulated operation set up in a working orthopaedi operating theatre.

Time - 1

Comment [MRR6]: I'm tempted to say the driver for this was the need to verify the smoke DVD produced by Augustine – remind them that this DVD was posted to all orthosurgeons in UK last year (assuming that is correct)

Comment [m7]: I'd be careful here. That might imply a strong corporate agenda behind these activities and raise questions as to the credibility of the results.



We compared forced air warming with a conductive fabric warming blanket, a different technology which uses conductive polymers to produce heat when powered with a specifically designed controller unit.

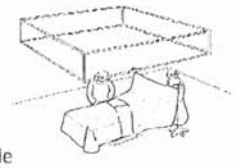
Forced air warming vents up to 800 watts of excess heat, whereas conductive fabric warming releases up to 100 watts of excess heat.

Comment [MRR8]: Are there any pictures of this in use with models? Ideally an attractive one!

Comment [m9]: I know the exact picture mike wants... I'll get it to you.

Comment [MRR10]: Need to mention the improved efficiency. Watts spend etc. Mark will have figures in comparison to FAW

Brent's animated



slide

A simulated operation was set up in a laminar flow operating theatre using a mannequin as a patient.
The patient was placed in the lateral position and the warming blanket placed over them.
They were then draped as standard for a modified Hardinge-approach hip replacement.

Comment [MRR11]: The picture needs to be changed a little so that one leg is above the drape.

Airflow was measured using neutral density soap bubbles. These hover suspended in still air, and their movement can be used to visualise flows within air currents. This is the bubble generating equipment...

Comment [MRR12]: Mention the helium bit

And here is the outlet emitting the neutral density bubbles

This is how the setup looked in the operating theatre.
The height of the anaesthesia screen was varied between experiements – I will detail the variations in setup in a moment

In this reverse angle shot you can see the bubble generator outlet

Within this setup, we were aiming to see if bubbles from the patient's head mobilised to the vicinity of the operative field, and whether any mobilisation was

Comment [MRR13]: Where the anaesthetist works..

altered by using forced air warming or conductive fabric warming. We also assessed whether the height of the anaesthesia screen altered this mobilisation.

The variables we altered then were:
Anaesthesia screen high, low or absent
Warming with Forced Air or Conductive fabric, the control was the conductive fabric blanket turned off

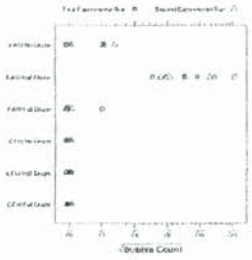
Time – 3:00

We randomised the experiment between these variables with separate set ups for each. Time was allowed between each experiment to allow things to cool down, and 5 minutes warm up was allowed at the beginning of each experimental run.

Comment [m14]: I'd ignore the statistical details of the experimental design. Those can be found in the paper and just add information that is not really relevant to the main story line. I'd stick to "layman" language where ever possible.

Results were taken by running the bubble generator as shown, and taking a digital photograph in the region of the operative field at 10 second intervals for one minute

Bubbles were counted in this region of the images for each setup. Any bubbles present in this zone had mobilised from the air surrounding the patient's head



Results:
The bubble counts were affected by the anaesthesia drape setting, with the half drape setup showing the largest effect.

Comment [MRR15]: Paul – very critical here that you take the trouble to explain exactly what this chart means. Put it in baby language and assume nothing. Start by describing each axis.

Setups using forced air warming showed more bubbles mobilised to the operative site than with conductive fabric warming.

The increase in bubbles with forced air warming was significant with the ether screen at half height and laid down; the increase was not significant with the full height ether screen

Comment [MRR16]: anaesthetic

? more elaboration on results – might be good to put a raw data table up
? more discussion about statistical model

Comment [m17]: Don't go into the statistics, really not needed and will take up too much time. That is for the paper.

This effect is quite striking when viewed in real time:

Video – half ether screen with bubbler running. Live narration

Video – CFW v FAW – abbreviated version of video on orthopodresearch blog comparing upward mobilisation of air from FAW with none from CFW	This video compares the warming technologies
Video – reverse angle lights and laminar flow	One last video clip, demonstrating the lack of laminar air flow under operating lights

Discussion

There are several points of interest.

Firstly, laminar flow may already be compromised, even in a highly performing operating theatre

Comment [MRR18]: highly performing?

Second, the high volume of heated air from forced air warming blankets is more than enough to overcome the overall downward effect of laminar flow

Third, placing a high anaesthesia screen protected against this phenomenon encountered when FAW was used, but using a half height screen potentiated it.

Using conductive fabric warming did not produce any detrimental effect, as it did not mobilise any air from the non sterile zone near the patient's head to the region of the operative field

Recommendations

We are conducting further studies to establish whether this effect is seen in different environments and with different operative setups.

This study prompted a change in Orthopaedic practice in wasbeck ~~Northumbria –~~ now all intraoperative patient warming is done with conductive fabric warming, and all ~~ether~~ anaethetic screens are at full height. This is being rolled out right across the Trust in all specialties but this is on a cost improvement programme basis.

Notes - ?for discussion, or to fit into main body

- 800+Watts of waste heat from FAW
- Mention spinal data, UofM study
- Mention infection data from Northumbria
- Mention filtration study

Comment [MRR19]: Nope only if asked

Comment [MRR20]: Suggest you hold this as the very last slide, - one that is placed after your thank you slide at the end. If you are lucky you can steer a question into exposing it. Normally work a treat and can be introduced with "I thought you might ask that.."

Comment [MRR21]: Nope. I think Sheffield are presenting particle counter stuff.

EXHIBIT DX28

TO DECLARATION OF COREY L. GORDON IN SUPPORT OF DEFENDANTS' OPPOSITION TO PLAINTIFFS' MOTIONS TO EXCLUDE TESTIMONY OF THEODORE HOLFORD AND JONATHAN BORAK

From: Mark <malbrecht@augbiomed.com>
To: 'Prof David Leaper' <profdavidleaper@doctors.org.uk>
CC: 'Scott Augustine' <saugustine@augbiomed.com>;'Mark Litchy' <mark@ctassociatesinc.com>;'Kumar Belani' <kumarbelani@gmail.com>;'Josh Waldman' <jwaldman@purezone.com>
Sent: 1/23/2010 12:00:49 AM
Subject: Article nearly ready for submission
Attachments: Figures_US.doc; Manuscript_US_rev_6.doc; Tables_US_manuscript.doc

David,
I'm just finishing the references (couple to go, will be done on Monday). You wanted to see the changes so here they are. Let me know if there are any other ways to improve this document. Expect a final copy early next week. As mentioned, we need you to be the corresponding author. Go ahead and make an account at the journal of american infection control. Provide me with the password-login and I'll begin the document upload (I have the native high-res figures here). Once I've done my part I'll have you finish the submission. Also, we need to be critically careful that this document appears to be impartial. Please re-read and let me know if there are any reasons suggesting that it may appear otherwise. If at all so, we should work to correct that before submission.

Thanks
-m

Also, Kumar I need you edits/suggestions. Please let me know what those may be. You can modify the updated document and figures.

Mark Albrecht
Augustine Biomedical & Design
6581 City West Parkway
Eden Prairie MN 55344

PH 952-465-3511

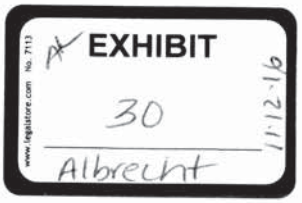


EXHIBIT DX29

TO DECLARATION OF COREY L. GORDON IN SUPPORT OF DEFENDANTS' OPPOSITION TO PLAINTIFFS' MOTIONS TO EXCLUDE TESTIMONY OF THEODORE HOLFORD AND JONATHAN BORAK

Implementing effective SSI surveillance

JULIE GILLSON and **GAIL LOWDON** provide an insight into how the Northumbria Healthcare NHS Foundation Trust reduced its infection rate within the orthopaedic department and developed a robust surgical site infection surveillance service.

In April 2004, after a number of years of voluntary monitoring, the Chief Medical Officer, made the surveillance of surgical site infection (SSI) in orthopaedic surgery mandatory.[1] There were certain criteria which included a minimum of three months data collection in at least one of the four orthopaedic categories.

- Total hip replacement (THR).
- Total Knee replacement (TKR).
- Hip Hemiarthroplasty (later changing to Repair Neck of Femur).
- Open reduction of long bone fractures.

The Health Protection Agency (HPA) reported a downward trend once this surveillance started in earnest; however there were a number of factors that may have affected how the data was reported across the different Trusts.[2] The length of stay of patients may differ as could the numbers of operations performed; the data collection was focused initially on hospital stay and did not include patients who developed an SSI once discharged home.

In 2008, hospitals were required by the HPA to identify and include patients who were readmitted with an SSI and further emphasis was put on organisations to use the data to evaluate local practice and institute changes where required.[3]

Northumbria Healthcare NHS Foundation Trust has three main sites with a number of small community hospitals and covers one of the largest geographical areas in the country providing health and social care to over 500,000 people living in Northumberland.

All three main sites and the orthopaedic teams performed the relevant orthopaedic surgery in the surveillance programme and a decision was made to monitor and report all three sites in three of the four categories 12 months a year.

During the last two quarters of 2008/2009, Northumbria Healthcare NHS Foundation Trust was reporting SSI rates in the combined total of surgeries in THR/TKR and Repair Neck of Femur between 3.5%-5% and was regularly receiving letters from the HPA informing the Trust of its high outlier status for SSI. As it was performing approximately 2,200 hip and knee replacements every year, implementing robust surveillance in SSI became a priority for the orthopaedic team and the Trust.

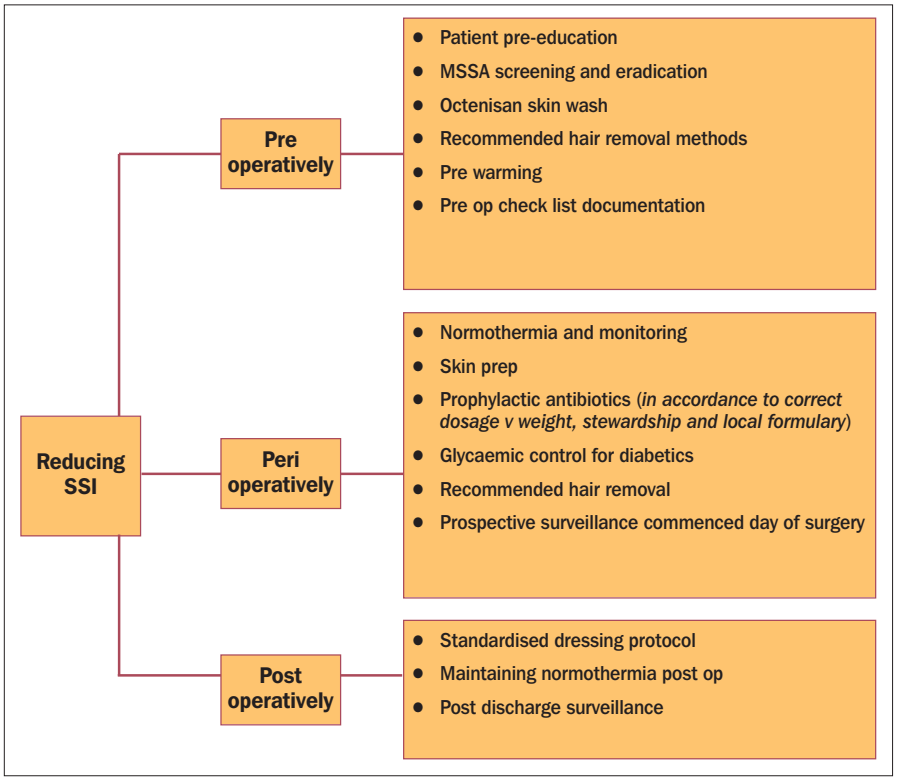


Figure 1: SSI Bundle Northumbria.

> 'We have introduced a strict theatre etiquette that is adhered to by all.'

The Northumbria SSI group

Following the correspondence from the HPA requesting action and the attendance of a group of clinical staff at an SSI conference in Birmingham, held by Patient Safety First, the SSI group was formed. A multi-disciplinary team formed the Trust SSI Group and the first meeting took place in December 2008. This group was chaired by a proactive orthopaedic surgeon and included consultant micro-biologist, senior managers, infection control leads, matrons and clinical leads from operating theatres.

Prior to the designated team of surveillance staff, surveillance of the mandatory reporting to the Health Protection Agency (as it was then known) was being completed by personnel while they were still doing their regular work. There was no ownership to the process of surveillance and the assurance in the validity of the results. The first action point of this meeting was to place a successful bid to appoint two full time SSI nurses on a 12 month secondment, therefore.

The commitment for the group was to ensure that the surveillance process that was put in place would be a robust and prospective surveillance. The initial aim was to bring the infection rate down and, by achieving this, ensure patient safety, and improved experience and outcomes, which we would be able to measure against the results we would later review from the post discharge surveillance and reported rates.

> 'One of the initiatives that has had the most impact has been the implementation of a Root Cause Analysis (RCA) tool that is completed for every patient found to have a deep infection.'

To date we have seen this group expand to include members from the estates department, community nursing, medical staff, anaesthetists and various other members of clinical specialities who join the group when review of practice is needed or new initiatives are being introduced.

The SSI bundle

In collaboration with The Institute for Healthcare improvement (IHI), Patient Safety First published an SSI bundle in 2009. This gave a checklist and a 'How to' guide aimed not only at clinicians but also at managers and allied health professionals to enable a multi-disciplinary approach to the worrying trend of increased SSIs.[4]

The SSI group decided to utilise this tool to develop a strategy to reduce the Trust's SSI rate. We divided the actions in to three major streams, pre-operative, peri-operative and post-operative with separate leads for each stream feeding back into the strategic SSI group as actions were completed.

There were many interventions that were seen as quick wins and small but significant changes were made and accepted by the wider teams – for example, the interventions performed by the pre-assessment team.

These included:

- Introduction of Octenisan wash that was given to all elective THR/TKR patients prior to surgery to be used at home, which has now been adopted at the point of care on the ward for trauma patients, prior to going to theatre.
- Adherence to the protocol on hair removal – it was often common practice for patients to be advised to have unnecessary shaves or use depilatory creams.

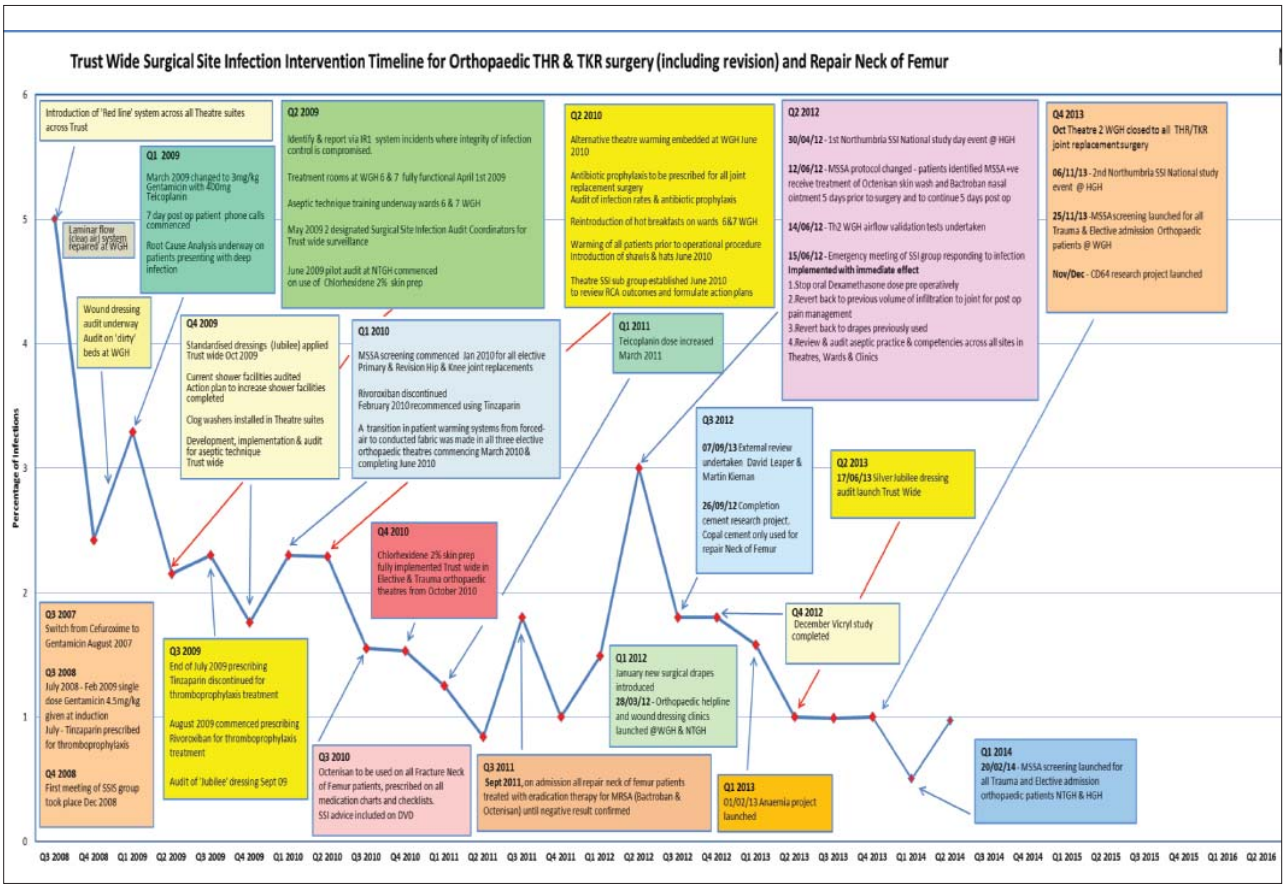


Figure 2: The 'Timeline' illustrates the interventions undertaken from 2008 to present day.

- Introduction of MSSA screening in 2010 for elective THR/TKR patients, which has now progressed, in 2014, to all elective and trauma orthopaedic patients admitted via A&E to the ward areas.
- Elective patients attend pre-surgery education class – this was developed to describe and advise the patient what to expect before during and after their surgery.

The two main areas that needed to be on board to make significant changes were the operating theatres and the orthopaedic wards both particularly challenging areas – with strong characters that needed to be persuaded to standardise and comply with the agreed interventions.

Theatres

Theatre etiquette in the Trust had changed over the last few decades, which had resulted in a more relaxed culture within this environment. Staff could come and go without being challenged and there was not a strict uniform policy in theatres and check lists, although available, were not effectively used.

This was by far the most challenging group of changes, as it did not just include theatre staff but also all of our surgeons – orthopaedic or otherwise. Meetings were held with the staff, education was provided by a named theatre sister, and the Operational Service Manager dealt with many individual concerns and complaints. However, over a period of time, the culture has changed and we have introduced a strict theatre etiquette that is adhered to by all.

The main changes that were required are as follows:

- Implementation of a red line near the entrance of theatre suite. This meant only essential staff could enter the operating theatres.
- Introduction of colour coded scrubs – a single designated colour scrub (raspberry) was to be worn by all who were required to work in or have access to the operating theatres. These must not be worn outside the theatre suite and this rule was incorporated into the Trust uniform policy.
- Review of current scrub techniques was undertaken and education and retraining was mandatory to all staff at all levels, ensuring standardisation of practice.
- Reducing and restricting the flow of staff through the operating theatre at the time of surgery.
- Stricter control of personal foot wear resulted in the introduction of new washable clogs and a built in clog washer, so staff could no longer wear their own clogs.
- Theatre audits – including monthly audit for compliance with the safer surgery check list and the High Impact Intervention no 4 – which evidenced compliance with the initiatives of pre op/peri op and post op.
- Re-commissioning and essential maintenance of all theatres. A formal report was fed back quarterly to the SSI group and specifically to the consultant microbiologist on the maintenance schedule/checks and status of all theatre suites.
- Antibiotics on induction – using appropriate prophylactic antibiotics in the correct dosage and time prior to incision.
- Peri-operative warming of patient and monitoring to maintain normothermia during surgery.

> 'The success has been down to an open but robust culture that has identified successes but has also accepted some failures.'

Orthopaedic wards

Our three orthopaedic sites functioned independently with inconsistent practices. As part of the SSI programme, senior clinicians and nursing staff agreed to standardise various practices and procedures. Changes were agreed at appropriate committees and Boards and disseminated to the wards by the Matrons who also monitored compliance. Actions included:

- Ensuring that all our surgical day wards had adequate shower facilities if required.
- Investment in appropriate ward based warming aids to use in pre-operative warming of patients to maintain normothermia before and after surgery.
- Reinstated designated treatment rooms at all sites on orthopaedic elective and trauma wards with the introduction of an air purification system (Radal air) in these rooms. Later on these rooms and systems were introduced to the outpatient departments also.
- Aseptic competencies review introduced – all nursing staff in all surgical areas now undertake a reassessment of their aseptic competencies every two years. Some training and education was also offered and taken up by senior medical staff.
- Standardisation of dressings across the organisation – introduction of a hydrocolloid/absorbent dressing (Aquacel Surgical). This dressing stays *in situ* for 14 days post op until clips/sutures are due for removal – thereby reducing manipulation of dressings and the potential introduction of bacteria to the wound through unnecessary dressing changes.

Other initiatives

Between 2009 and the present, many other initiatives were discussed and implemented. Some were small changes that improved the patient pathway; others were more progressive and have made a significant difference to patient outcomes.

Root cause analysis

One of the initiatives that has had the most impact has been the implementation of a Root Cause Analysis (RCA) tool that is completed for every patient found to have a deep infection. The first of these tools was introduced by the consultant microbiologist of the SSI group, which has since been developed and evolved to the version that is in use today.

The initial completion of the RCA is undertaken by the SSI nurses and it is then distributed to all members of the team via email. This email allows an open and honest dialogue about the patient treatment and condition. All and any members of the team are encouraged to participate and comment on any part of the patient's journey from pre-op to post-operative. This has proven to be a fantastic source of information allowing all levels of staff to contribute to the analysis of the potential causal factors involved.

Weekly surveillance grid

A weekly report is sent to the multi-disciplinary team (MDT) via email to highlight patients that the SSI team have identified as at risk of infection or other complications, which is a form of 'watch and wait'.

'The SSI group has been successful in reducing the infection rate at Northumbria Healthcare from 5% to 0.9% (April – June 2014).'

Weekly revision MDT meeting

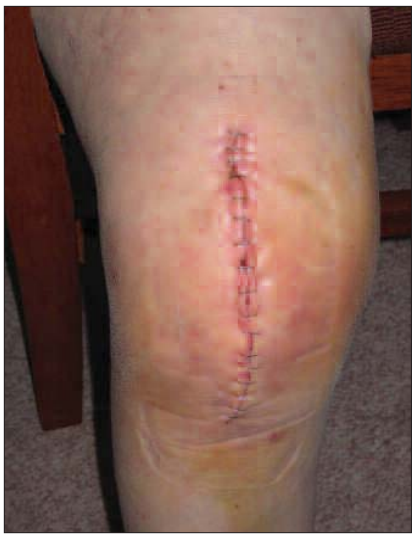
Any patient who has had a complication to their joint replacement that requires further interventions or surgery will be discussed at this weekly meeting. The consultant orthopaedic surgeon and microbiologist will identify patients with potential or existing infections and agree an appropriate management plan for these individuals.

Discharge call to patient

Initially started in 2007, supporting an enhanced recovery programme in THR/TKR, a seven day call has now progressed to a call made at two days post discharge by the SSI nurses ensuring patients have no wound issues and there is also an opportunity to discuss any other concerns patients may have.

Orthopaedic helpline

Introduced in 2010, as an initiative by the Preventing Readmission Group, this helpline was open to both patients and community colleagues providing information and advice on the management of our orthopaedic post-operative patients. This has been hugely successful in identifying early or potential infections and providing appropriate management plans, including antibiotic stewardship. It is important to highlight the need for appropriate and qualified personnel to be employed within the SSI role as there is active clinical advice and intervention plans are implemented. Since the helpline launch in April 2012 to January 2014 it has taken 2,353 calls with 523 patients referred to the wound clinics (22% patients to the clinic with 78% patients concerns resolved over the phone). Following this success, the helpline is to be extended to all surgical patients in October 2014.



www.wikipedia.org Ravedave CC-BY-SA-3.0

Wound clinics

Within the out-patients departments an open access nurse-led clinic has been set up to review patients with concerns about their wounds. This was regulated by the orthopaedic help line who would refer patients to the clinic after telephone consultation.

30 day phone call

We embraced the Public Health England (previously HPA) recommendation to contact patient on, or around, 30 days after their operation to identify potential complications (primarily infections) and ensure robust reporting of SSI.[5]

Patient experience

A very important element in the development of the services to our patients has been the inclusion of patient experience feedback where we actively encourage our patients to join our steering groups in the project work and they actively participate in our educational study events.

Road shows

Our community services cover a large geographical area and incorporate two different commissioning groups, so communication to this widespread group of staff was challenging and had failed in the past. A strategy was developed to enable our teams to visit key community bases to share the changes that would impact upon their management of at risk patients. A package was developed by the SSI nurses to facilitate training and education to the community staff.

Present

The SSI group has been successful in reducing the infection rate at Northumbria Healthcare from 5% to 0.9% (April – June 2014). It has been challenging at times, but the success has been down to an open but robust culture that has identified successes but has also accepted some failures.

However, we are not complacent and continue to maintain motivation within the staff groups and encourage colleagues within the other specialties to participate in the service, for the benefit of their patients and staff development.

The SSI surveillance team has grown and we now have a lead nurse, two other surveillance nurses and administrative support. The meetings continue and active surveillance is paramount. The most recent developments include the monitoring of Breast and C-Section patients with the relevant surgeons following the lead from their orthopaedic colleagues.

The SSI team have won a number of awards for their efforts including:

- HAI watchdog awards 2011 Operating Theatre Infection Prevention Initiative.
- Safer Care Northeast 2011/2012 Initiatives reducing SSI in HAI.
- Improving patient experience through Effective Communication with Patients and Families 2013.

This team is highly respected within the organisation and continues to deliver a successful service.

In 2011, an internal study day was held by Northumbria Healthcare NHS Foundation Trust with the intention of sharing our developments and training package. This has now evolved into a national yearly event and, this year, is being held on the 22nd October 2014 at The Marriot Hotel Gosforth Newcastle. More details can be found on the following website www.qist.co.uk

References

1 Chief Medical Officer. *Surveillance of Healthcare Associated Infections PL/CMO/2003/4*. London: Department of Health. 9 June 2003.

2 Health Protection Agency. *Mandatory surveillance of surgical site infection in orthopaedic surgery. April 2004 to March 2005*. London: Health Protection Agency.

3 Health Protection Agency. Fifth report of the mandatory surveillance of surgical site infection in orthopaedic surgery. April 2004 to March 2009. London: Health Protection Agency December 2009.

4 Patient Safety First. *The 'How to' Guide for Reducing Harm in Perioperative Care*. Version 2, 2009. www.patientsafetyfirst.nhs.uk

5 Public Health England. *Protocol for the Surveillance of Surgical Site Infection*. Version 6. June 2013.

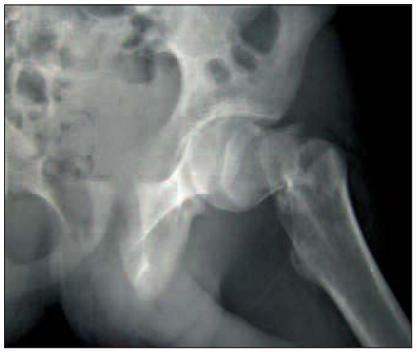


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EXHIBIT DX30

TO DECLARATION OF COREY L. GORDON IN SUPPORT OF DEFENDANTS' OPPOSITION TO PLAINTIFFS' MOTIONS TO EXCLUDE TESTIMONY OF THEODORE HOLFORD AND JONATHAN BORAK

Volume 03 / Issue 03 / September 2015 boa.ac.uk

Prevention of Periprosthetic Joint Infection

Ramsay Refaie, Simon Jameson and Mike Reed

Periprosthetic joint infection (PJI) can be a catastrophic complication following joint replacement surgery. The financial costs and morbidity associated with PJI are well established[1-3] with evidence now emerging that PJI is an independent risk factor for mortality[4]. Prevention is better than cure and whilst an exhaustive list is beyond the scope of this article we will discuss some offbeat tactics to consider in practice.


Ramsay Refaie


Simon Jameson


Mike Reed

The Basis of the Problem

When Charnley wrote about prosthetic joint infection in 1969 he stated there was "still uncertainty as to how often a wound is infected in the operating room and how often at a later date during the healing of the wound"[5]. This same uncertainty still persists to this day. Contaminants may arise from the patient's skin, from the surgical personnel or from the surgical instrumentation itself[6, 7]. It is likely that almost all surgical wounds are contaminated because skin preparation at the time of surgery will only decontaminate the skin surface and bacteria will remain in deeper layers of the skin[8]. Whilst it is also possible for infection to seed to the implant in haematogenous spread or so called "metastatic infection"[9] this occurs less frequently. Gram-positive organisms are the most commonly reported with *Staphylococcus aureus* accounting for over a third of reported PJIs in England and Wales[10].

Broadly speaking prevention strategies target modifiable patient factors and peri-operative factors; these are summarised in Table 1. Many of these tactics are presented at open events with The Quality Improvement in Surgical Teams initiative[11].

Volume 03 / Issue 03 / September 2015 boa.ac.uk

Journal of Trauma and Orthopaedics: Volume 03, Issue 03, pages 50-52
Title: Prevention of Periprosthetic Joint Infection
Authors: Ramsay Refaie, Simon Jameson and Mike Reed

Risk Factor	Management
Patient factors	
Inflammatory arthritis	• Disease-modifying anti-rheumatic drugs (DMARDs) including methotrexate should be discussed with the prescriber • Peri-operative steroids are generally not required • Balance the risks and benefits of stopping anti-TNF – stop at 3-5 half-lives pre-operatively, restart after wound healing and no evidence of infection
Obesity	• Dietician input to encourage weight loss • Adjust peri-operative antibiotic doses appropriately • In super-obese consider bariatric surgery prior to joint replacement surgery
Smoking	• Consider a smoking cessation programme
Methicillin Resistant and Methicillin Sensitive Staphylococcus aureus carriage (MRSA and MSSA)	• Screening based on local guidelines, and decolonise prior to surgery
Peri-operative factors	
Patient preparation	• Shower on day of surgery • If hair removal required, use electric clippers on day of surgery • Avoid oil-based skin moisturisers
Antibiotics	• Prophylactic antibiotics should be given as early as possible in the anaesthetic room • If cementation is required, antibiotic-impregnated cement should be used • There is little consensus or evidence for which antibiotic prophylaxis
Theatre	• Use laminar flow where possible • Keep theatre door opening to a minimum
Personnel	• Hand wash with antiseptic surgical solution, using a single-use brush or pick for the nails • Before subsequent operations hands should be washed with either an alcoholic hand rub or an antiseptic surgical solution • Use scrub staff assisted glove donning • Double glove and change gloves regularly
Skin preparation	• Use an alcohol pre-wash followed by a 2% chlorhexidine-alcohol scrub solution, or alcoholic betadine. Beware of fires
Anaesthetic	• Maintain normothermia • Maintain normovolaemia • A higher inspired oxygen concentration peri-operatively and for 6 hours post-operative may be of benefit

Table 1: *Summary table of common prevention tactics*

Proven strategies and some food for thought

MSSA screening and decontamination

Methicillin Resistant *Staphylococcus aureus* (MRSA) is the emotive "superbug" that every patient seems to fear. Indeed MRSA infections have been shown to have significantly higher treatment costs than other causal organisms of PJI[12]. MRSA screening is now well established across the NHS with positive results prompting decolonisation prior to surgery. However, nasal carriage of Methicillin sensitive organisms (MSSA) also confers an increased risk of PJI. Carriage is common (~20%)[13] and decolonisation presents us with an easy "high yield" strategy in the fight against PJI. A large, randomised, placebo controlled multi-centre trial published in the New England Journal of Medicine in 2010 showed that decolonisation of MSSA carriers with mupirocin nasal ointment and chlorhexidine soap prior to orthopaedic and cardiothoracic surgery reduced their risk of MSSA SSI by almost 60% from 7.7% to 3.4%[13]. This strategy has also been shown to be cost effective[14]. Despite this, many centres still do not routinely screen for MSSA. After MSSA screening and decolonisation was introduced in one NHS joint replacement unit, MSSA infections reduced from 0.84% to 0.26% - the caveat being there were other infection prevention methods implemented during the time period[15].

Smoking cessation

Smokers are at increased risk of wound complications and infections[16]. A randomised controlled trial from Denmark, published in the Lancet, has shown that cessation or at least 50% reduction in smoking decreased wound complications from 31% to 5% ($p<0.001$) in patients undergoing hip and knee arthroplasty[17]. Smoking cessation should be considered for all patients.

Patient warming

Pre warming of patients before theatre is a proven strategy for preventing hypothermia intra-operatively and in recovery[18, 19]. A large RCT from the UK published in the Lancet showed that pre warming reduced the risk of infection by around 65% in clean surgery[20]. Despite this pre warming is still not widely adopted in UK centres.

Intra-operative warming is widely performed but the method of intra-operative patient warming may also alter the risk of infection during clean air surgery[21]. Randomised studies have demonstrated that the popular forced air warming devices interact with laminar air flow currents in such a way that non-filtered air can be drawn from outside the clean air canopy into the wound area[22, 23]. Our own switch to the alternative conductive fabric warming led to a significant decrease in deep infection rates[22]. These concepts are best demonstrated in high definition video *(www.youtube.com/user/orthopodresearch)*.

Laminar flow and lights

Historical evidence has shown that laminar flow in combination with antibiotic prophylaxis reduces infection rates in joint arthroplasty[24]. Recently however, the benefit of laminar flow has come into question[10, 25, 26].

Given the fragile nature of laminar air flow, we wanted to investigate the impact of popular suspended theatre lights. In a series of experiments using neutrally buoyant helium bubbles we evaluated the efficacy of laminar flow at clearing particles from the operative field looking specifically at the impact of lights. These experiments

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are best viewed in high definition video *(www.youtube.com/user/orthopodresearch)*. Perhaps unsurprisingly we found that placing lights directly above the operative field impairs the ability of the system to clear airborne particles. Figure 1 shows the rate at which particles were cleared from the operative field after one minute of filling with bubbles. No lights, a single light and two lights over a mannequin knee (Figure 2) were evaluated. This provides further evidence for the intuitive interactions between laminar air flow currents and objects within it. Based on this the lead author has joined several others who operate without suspended theatre lights for knee replacement. Hugh Howorth and Sir John Charnley worked closely to develop the optimal operating environment. The original greenhouse used by Charnley contained two banks of lights to illuminate the operative field[27]. Subsequent Howorth/Charnley theatre designs contained banks of lights outside the laminar flow canopy. The theatre picture of Wrightington Hospital (Figure 3) clearly shows a bank of lights outside the laminar flow enclosure. Whilst this approach is not for everyone, an awareness of the potential interactions with laminar flow and attempts to minimise these should be encouraged.

Targeted antibiotic prophylaxis

The benefits of prophylactic antibiotics are widely accepted across most surgical specialties[28, 29]. Prophylaxis is however not without risks and the potential reduction in SSIs must be balanced against the adverse effects of antibiotics. Cephalosporins, once a panacea in our prophylactic armamentarium, have fallen out of favour in the UK largely due to their association with Clostridium difficile associated diarrhoea (CDAD), despite this representing a relatively minor complication

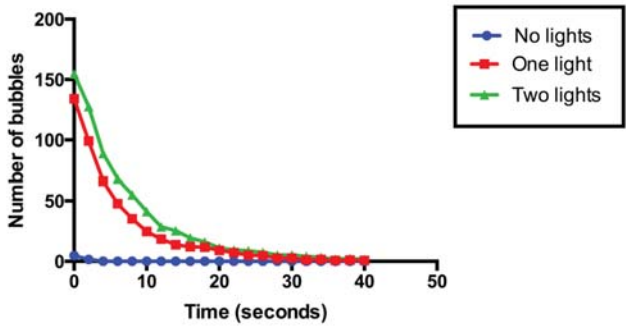

Figure 1: *Rate of bubble clearance*

Figure 2: *Knee mannequin with bubbles being introduced*

Figure 3: *Old Theatre 1 at Wrightington Hospital*

in elective orthopaedic surgery (1.7 per 1000)[30]. A systematic review reported that there is insufficient evidence of a significant difference between cephalosporins, teicoplanin or penicillin derivatives[31]. In practice, most prophylactic regimens are now based on dual therapy yet these are frequently associated with higher incidence of acute kidney injury and no change in rates of PJI[32-35]. Elsewhere, gentamicin alone has also been shown to offer no benefit in terms of reducing CDAD[36]. With all this confusion a large randomised trial is required to best protect our patients undergoing primary joint replacement.

Summary

PJI is catastrophic and every feasible step should be taken to prevent this. Whilst this article is not exhaustive it may encourage achievable strategies to reduce the incidence of PJI. ■

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Simon Jameson is currently Robin Ling Hip Fellow at the Princess Elizabeth Orthopaedic Centre in Exeter. He trained on the Northern and Glasgow Orthopaedic rotations. He is a past NJR research fellow with an MD thesis focused on outcomes after primary hip replacement.

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References can be found online at *www.boa.ac.uk/publications/JTO* or by scanning the QR Code.

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EXHIBIT DX31

TO DECLARATION OF COREY L. GORDON IN SUPPORT OF DEFENDANTS' OPPOSITION TO PLAINTIFFS' MOTIONS TO EXCLUDE TESTIMONY OF THEODORE HOLFORD AND JONATHAN BORAK

Christopher Nachtsheim <nacht001@umn.edu>

Publication Factory Continues

1 message

Mark <malbrecht@augbiomed.com> Fri, Jul 9, 2010 at 3:44 PM
To: "Reed Mike (Northumbria Health Care NHS Trust)" <mike.reed@nhs.net>, Paul McGovern <pdmcgovern@gmail.com>
Cc: Scott Augustine <saugustine@augbiomed.com>, Andreas Deibel <adeibel@augbiomed.com>, Keith Leland <kleland@augbiomed.com>, rhumble@augbiomed.com, Christopher Nachtsheim <nacht001@umn.edu>

Paul and Mike,

At this point in time we have 3 completed manuscripts that are ready to be submitted for publication that you are both authors on:

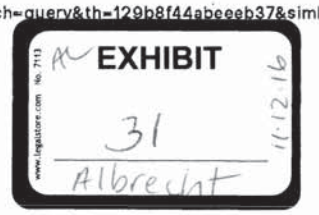
1) An Evaluation Of Filtration Adequacy And Airborne Contamination Emissions From Next Generation Forced Air Warming Blowers. *Target Journal: British Journal of Bone and Joint Surgery*

2) Forced Air Warming versus Conductive Fabric Warming – An Evaluation of Conventional (non-laminar, positive pressure) Operating Room Ventilation Disruption. *Target Journal: US Annals or Archives of Surgery*

3) Forced Air Warming versus Conductive Fabric Warming – An Evaluation of Laminar Operating Room Ventilation Disruption. *Target Journal: Undecided. This is the most complete piece of work on laminar flow disruption and should go to a top tier journal.*

I've already sent both of you articles 1 & 2; article 3 is a new one and, arguably, the best of the three. When I'm in the UK next week I'd like to plan a time (the week of July 19th through 26th) for us to get together, agree on reviews, and submit these articles to 3 appropriate journals. I'd be willing to come up to Northumbria for these purposes.

Also, Dr Andrew Legg has invited you guys to Sheffield hospital the weekend of July 17th and 18th to help with the research effort there. If you are interested the company would be willing to cover your hotel and expenses. Let me know and I'll work to book arrangements. Also, I'm available to conduct further research in Northumbria the dates July 19th -26th. I have the equipment available for your use on those dates. Maybe we could brainstorm some interesting



research ideas.

I'll be available via e-mail this weekend.

Thanks

-Mark

P.S. Paul, I'll work to get some charts together for the 2 studies you sent to me that we can, hopefully, discuss in person.

Mark Albrecht

Augustine Biomedical & Design

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PH 952-465-3511

3 attachments

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526K

Conventional_Vent_Manuscript_7-2.doc
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Manuscript_Laminar_7-9.doc
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EXHIBIT DX32

TO DECLARATION OF COREY L. GORDON IN SUPPORT OF DEFENDANTS' OPPOSITION TO PLAINTIFFS' MOTIONS TO EXCLUDE TESTIMONY OF THEODORE HOLFORD AND JONATHAN BORAK

thebmj

Editorials

Wakefield's article linking MMR vaccine and autism was fraudulent

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Fiona Godlee, editor in chief, Jane Smith, deputy editor, Harvey Marcovitch, associate editor
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Clear evidence of falsification of data should now close the door on this damaging vaccine scare

"Science is at once the most questioning and . . . sceptical of activities and also the most trusting," said Arnold Relman, former editor of the *New England Journal of Medicine*, in 1989. "It is intensely sceptical about the possibility of error, but totally trusting about the possibility of fraud."**1** Never has this been truer than of the 1998 *Lancet* paper that implied a link between the measles, mumps, and rubella (MMR) vaccine and a "new syndrome" of autism and bowel disease.⇓

Figure1

Authored by Andrew Wakefield and 12 others, the paper's scientific limitations were clear when it appeared in 1998.**2 3** As the ensuing vaccine scare took off, critics quickly pointed out that the paper was a small case series with no controls, linked three common conditions, and relied on parental recall and beliefs.**4** Over the following decade, epidemiological studies consistently found no evidence of a link between the MMR vaccine and autism.**5 6 7 8** By the time the paper was finally retracted 12 years later,**9** after forensic dissection at the General Medical Council's (GMC) longest ever fitness to practise hearing,**10** few people could deny that it was fatally flawed both scientifically and ethically. But it has taken the diligent scepticism of one man, standing outside medicine and science, to show that the paper was in fact an elaborate fraud.

In a series of articles starting this week, and seven years after first looking into the MMR scare, journalist Brian Deer now shows the extent of Wakefield's fraud and how it was perpetrated (doi:10.1136/bmj.c5347). Drawing on interviews, documents, and data made public at the GMC hearings, Deer shows how Wakefield altered numerous facts about the patients' medical histories in order to support his claim to have identified a new syndrome; how his institution, the Royal Free Hospital and Medical School in London, supported him as he sought to exploit the ensuing MMR scare for financial gain; and how key players failed to investigate thoroughly in the public interest when Deer first raised his concerns.**11**

Deer published his first investigation into Wakefield's paper in 2004.**12** This uncovered the possibility of research fraud, unethical treatment of children, and Wakefield's conflict of interest through his involvement with a lawsuit against manufacturers of the MMR vaccine. Building on these findings, the GMC launched its own proceedings that focused on whether the research was ethical. But while the disciplinary panel was examining the children's medical

records in public, Deer compared them with what was published in the *Lancet*. His focus was now on whether the research was true.

The Office of Research Integrity in the United States defines fraud as fabrication, falsification, or plagiarism.[13] Deer unearthed clear evidence of falsification. He found that not one of the 12 cases reported in the 1998 *Lancet* paper was free of misrepresentation or undisclosed alteration, and that in no single case could the medical records be fully reconciled with the descriptions, diagnoses, or histories published in the journal.

Who perpetrated this fraud? There is no doubt that it was Wakefield. Is it possible that he was wrong, but not dishonest: that he was so incompetent that he was unable to fairly describe the project, or to report even one of the 12 children's cases accurately? No. A great deal of thought and effort must have gone into drafting the paper to achieve the results he wanted: the discrepancies all led in one direction; misreporting was gross. Moreover, although the scale of the GMC's 217 day hearing precluded additional charges focused directly on the fraud, the panel found him guilty of dishonesty concerning the study's admissions criteria, its funding by the Legal Aid Board, and his statements about it afterwards.[14]

Furthermore, Wakefield has been given ample opportunity either to replicate the paper's findings, or to say he was mistaken. He has declined to do either. He refused to join 10 of his coauthors in retracting the paper's interpretation in 2004,[15] and has repeatedly denied doing anything wrong at all. Instead, although now disgraced and stripped of his clinical and academic credentials, he continues to push his views.[16]

Meanwhile the damage to public health continues, fuelled by unbalanced media reporting and an ineffective response from government, researchers, journals, and the medical profession.[17] [18] Although vaccination rates in the United Kingdom have recovered slightly from their 80% low in 2003-4,[19] they are still below the 95% level recommended by the World Health Organization to ensure herd immunity. In 2008, for the first time in 14 years, measles was declared endemic in England and Wales.[20] Hundreds of thousands of children in the UK are currently unprotected as a result of the scare, and the battle to restore parents' trust in the vaccine is ongoing.

Any effect of the scare on the incidence of mumps remains in question. In epidemics in the UK, the US, and the Netherlands, peak prevalence was in 18-24 year olds, of whom 70-88% had been immunised with at least one dose of the MMR vaccine.[21] [22] Any consequence of a fall in uptake after 1998 may not become apparent until the cohorts of children affected reach adolescence. One clue comes from an outbreak in a school in Essen, Germany, attended by children whose parents were opposed to vaccinations. Of the 71 children infected with mumps, 68 had not been immunised.[23]

But perhaps as important as the scare's effect on infectious disease is the energy, emotion, and money that have been diverted away from efforts to understand the real causes of autism and how to help children and families who live with it.[24]

There are hard lessons for many in this highly damaging saga. Firstly, for the coauthors. The GMC panel was clear that it was Wakefield alone who wrote the final version of the paper. His coauthors seem to have been unaware of what he was doing under the cover of their names and reputations. As the GMC panel heard, they did not even know which child was which in the paper's patient anonymised text and tables. However, this does not absolve them. Although only two (John Walker-Smith and Simon Murch) were charged by the GMC, and only one, the paper's senior author Walker-Smith, was found guilty of misconduct, they all failed in their duties as authors. The satisfaction of adding to one's CV must never detract from the responsibility to ensure that one has been neither party to nor duped by a fraud. This means that coauthors will have to check the source data of studies more thoroughly than

many do at present—or alternatively describe in a contributor's statement precisely which bits of the source data they take responsibility for.

Secondly, research ethics committees should not only scrutinise proposals but have systems to check that what is done is what was permitted (with an audit trail for any changes) and work to a governance procedure that can impose sanctions where an eventual publication proves this was not the case. Finally, there are lessons for the Royal Free Hospital, the *Lancet*, and the wider scientific community. These will be considered in forthcoming articles.

What of Wakefield's other publications? In light of this new information their veracity must be questioned. Past experience tells us that research misconduct is rarely isolated behaviour.**25** Over the years, the *BMJ* and its sister journals *Gut* and *Archives of Disease in Childhood* have published a number of articles, including letters and abstracts, by Wakefield and colleagues. We have written to the vice provost of UCL, John Tooke, who now has responsibility for Wakefield's former institution, to ask for an investigation into all of his work to decide whether any more papers should be retracted.

The *Lancet* paper has of course been retracted, but for far narrower misconduct than is now apparent. The retraction statement cites the GMC's findings that the patients were not consecutively referred and the study did not have ethical approval, leaving the door open for those who want to continue to believe that the science, flawed though it always was, still stands. We hope that declaring the paper a fraud will close that door for good.

Notes

Cite this as: *BMJ* 2011;342:c7452

Footnotes

- Feature, doi:10.1136/bmj.c5347
- Competing interests: All authors have completed the Unified Competing Interest form at www.icmje.org/coi_disclosure.pdf (available on request from the corresponding author) and declare: no support from any organisation for the submitted work; no financial relationships with any organisations that might have an interest in the submitted work in the previous three years. HM chairs GMC fitness to practise panels. He had no association with the Wakefield hearings and the views expressed in this article are his own and do not represent those of the GMC.
- Provenance and peer review: Commissioned; not externally peer reviewed.

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EXHIBIT DX33

TO DECLARATION OF COREY L. GORDON IN SUPPORT OF DEFENDANTS' OPPOSITION TO PLAINTIFFS' MOTIONS TO EXCLUDE TESTIMONY OF THEODORE HOLFORD AND JONATHAN BORAK

Early report

Ileal-lymphoid-nodular hyperplasia, non-specific colitis, and pervasive developmental disorder in children

A J Wakefield, S H Murch, A Anthony, J Linnell, D M Casson, M Malik, M Berelowitz, A P Dhillon, M A Thomson, P Harvey, A Valentine, S E Davies, J A Walker-Smith

Summary

Background We investigated a consecutive series of children with chronic enterocolitis and regressive developmental disorder.

Methods 12 children (mean age 6 years [range 3–10], 11 boys) were referred to a paediatric gastroenterology unit with a history of normal development followed by loss of acquired skills, including language, together with diarrhoea and abdominal pain. Children underwent gastroenterological, neurological, and developmental assessment and review of developmental records. Ileocolonoscopy and biopsy sampling, magnetic-resonance imaging (MRI), electroencephalography (EEG), and lumbar puncture were done under sedation. Barium follow-through radiography was done where possible. Biochemical, haematological, and immunological profiles were examined.

Findings Onset of behavioural symptoms was associated by the parents, with measles, mumps, and rubella vaccination in eight of the 12 children, with measles infection in one child, and otitis media in another. All 12 children had intestinal abnormalities ranging from lymphoid nodular hyperplasia to aphthoid ulceration. Histology showed patchy chronic inflammation in 11 children and reactive ileal lymphoid hyperplasia in seven, but no granulomas. Behavioural disorders included autism (nine), disintegrative psychosis (one), and possible postviral or vaccinal encephalitis (two). There were no focal neurological abnormalities and MRI and EEG tests were normal. Abnormal laboratory results were significantly raised urinary methylmalonic acid compared with age-matched controls ($p=0.003$), low haemoglobin in four children, and low serum IgA in four children.

Interpretation We identified associated gastrointestinal disease and developmental regression in a group of previously normal children, which was generally associated in time with possible environmental triggers.

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See Commentary page

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Introduction

We saw several children who, after a period of apparent normality, lost acquired skills, including communication. They all had gastrointestinal symptoms, including abdominal pain, diarrhoea, and bloating and, in some cases, food intolerance. We describe the clinical findings, and gastrointestinal features of these children.

Patients and methods

12 children, consecutively referred to the department of paediatric gastroenterology with a history of a pervasive developmental disorder with loss of acquired skills and intestinal symptoms (diarrhoea, abdominal pain, bloating and food intolerance), were investigated. All children were admitted to the ward for 1 week, accompanied by their parents.

Clinical investigations

We took histories including details of immunisations and exposure to infectious diseases, and assessed the children. In 11 cases the history was obtained by the senior clinician (JW-S). Neurological and psychiatric assessments were done by consultant staff (PH, MB) with HMS-4 criteria.[1] Developmental review included a review of prospective developmental records from parents, health visitors, and general practitioners. Four children did not undergo psychiatric assessment in hospital; all had been assessed professionally elsewhere, so these assessments were used as the basis for their behavioural diagnosis.

After bowel preparation, ileocolonoscopy was performed by SHM or MAT under sedation with midazolam and pethidine. Paired frozen and formalin-fixed mucosal biopsy samples were taken from the terminal ileum; ascending, transverse, descending, and sigmoid colons, and from the rectum. The procedure was recorded by video or still images, and were compared with images of the previous seven consecutive paediatric colonoscopies (four normal colonoscopies and three on children with ulcerative colitis), in which the physician reported normal appearances in the terminal ileum. Barium follow-through radiography was possible in some cases.

Also under sedation, cerebral magnetic-resonance imaging (MRI), electroencephalography (EEG) including visual, brain stem auditory, and sensory evoked potentials (where compliance made these possible), and lumbar puncture were done.

Laboratory investigations

Thyroid function, serum long-chain fatty acids, and cerebrospinal-fluid lactate were measured to exclude known causes of childhood neurodegenerative disease. Urinary methylmalonic acid was measured in random urine samples from eight of the 12 children and 14 age-matched and sex-matched normal controls, by a modification of a technique described previously.[2] Chromatograms were scanned digitally on computer, to analyse the methylmalonic-acid zones from cases and controls. Urinary methylmalonic-acid concentrations in patients and controls were compared by a two-sample *t* test. Urinary creatinine was estimated by routine spectrophotometric assay.

Children were screened for antiendomyseal antibodies and boys were screened for fragile-X if this had not been done

Child	Age (years)	Sex	Abnormal laboratory tests	Endoscopic findings	Histological findings
1	4	M	Hb 10·8, PCV 0·36, WBC 16·6 (neutrophilia), lymphocytes 1·8, ALP 166	Ileum not intubated; aphthoid ulcer in rectum	Acute caecal cryptitis and chronic non-specific colitis
2	9·5	M	Hb 10·7	LNH of T ileum and colon; patchy loss of vascular pattern; caecal aphthoid ulcer	Acute and chronic non-specific colitis: reactive ileal lymphoid hyperplasia
3	7	M	MCV 74, platelets 474, eosinophils 2·68, IgE 114, IgG_4 8·4	LNH of T ileum	Acute and chronic non-specific colitis: reactive ileal and colonic lymphoid hyperplasia
4	10	M	IgE 69, IgG_1 8·25, IgG_4 1·006, ALP 474, AST 50	LNH of T ileum; loss of vascular pattern in rectum	Chronic non-specific colitis: reactive ileal and colonic lymphoid hyperplasia
5	8	M		LNH of T ileum; proctitis with loss of vascular pattern	Chronic non-specific colitis: reactive ileal lymphoid hyperplasia
6	5	M	Platelets 480, ALP 207	LNH of T ileum; loss of colonic vascular pattern	Acute and chronic non-specific colitis: reactive ileal lymphoid hyperplasia
7	3	M	Hb 9·4, WBC 17·2 (neutrophilia), ESR 16, IgA 0·7	LNH of T ileum	Normal
8	3·5	F	IgA 0·5, IgG 7	Prominent ileal lymph nodes	Acute and chronic non-specific colitis: reactive ileal lymphoid hyperplasia
9	6	M		LNH of T ileum; patchy erythema at hepatic flexure	Chronic non-specific colitis: reactive ileal and colonic lymphoid hyperplasia
10	4	M	IgG_1 9·0	LNH of T ileum and colon	Chronic non-specific colitis: reactive ileal lymphoid hyperplasia
11	6	M	Hb 11·2, IgA 0·26, IgM 3·4	LNH of T ileum	Chronic non-specific colitis
12	7	M	IgA 0·7	LNH on barium follow-through; colonoscopy normal; ileum not intubated	Chronic non-specific colitis: reactive colonic lymphoid hyperplasia

LNH=lymphoid nodular hyperplasia; T ileum=terminal ileum. Normal ranges and units: Hb=haemoglobin 11·5–14·5 g/dL; PCV=packed cell volume 0·37–0·45; MCV=mean cell volume 76–100 pg/dL; platelets 140–400 10^9/L; WBC=white cell count 5·0–15·5 10^9/L; lymphocytes 2·2–8·6 10^9/L; eosinophils 0·04–0·4 10^9/L; ESR=erythrocyte sedimentation rate 0–15 mm/h; IgG 8–18 g/L; IgG_1 3·53–7·25 g/L; IgG_4 0·1–0·99 g/L; IgA 0·9–4·5 g/L; IgM 0·6–2·8 g/L; IgE 0–62 g/L; ALP=alkaline phosphatase 35–130 U/L; AST=aspartate transaminase 5–40 U/L.

Table 1: **Clinical details and laboratory, endoscopic, and histological findings**

before. Stool samples were cultured for *Campylobacter* spp, *Salmonella* spp, and *Shigella* spp and assessed by microscopy for ova and parasites. Sera were screened for antibodies to *Yersinia enterocolitica*.

Histology

Formalin-fixed biopsy samples of ileum and colon were assessed and reported by a pathologist (SED). Five ileocolonic biopsy series from age-matched and site-matched controls with reports showed histologically normal mucosa were obtained for comparison. All tissues were assessed by three other clinical and experimental pathologists (APD, AA, AJW).

Ethical approval and consent

Investigations were approved by the Ethical Practices Committee of the Royal Free Hospital NHS Trust, and parents gave informed consent.

Results

Clinical details of the children are shown in tables 1 and 2. None had neurological abnormalities on clinical examination; MRI scans, EEGs, and cerebrospinal-fluid profiles were normal; and fragile X was negative. Prospective developmental records showed satisfactory achievement of early milestones in all children. The only girl (child number eight) was noted to be a slow developer compared with her older sister. She was subsequently found to have coarctation of the aorta. After surgical repair of the aorta at the age of 14 months, she progressed rapidly, and learnt to talk. Speech was lost later. Child four was kept under review for the first year of life because of wide bridging of the nose. He was discharged from follow-up as developmentally normal at age 1 year.

In eight children, the onset of behavioural problems had been linked, either by the parents or by the child's physician, with measles, mumps, and rubella vaccination. Five had had an early adverse reaction to immunisation (rash, fever, delirium; and, in three cases, convulsions). In these eight children the average interval from exposure to first behavioural symptoms was 6·3 days (range 1–14). Parents were less clear about the timing of onset of abdominal symptoms because children were not toilet trained at the time or because behavioural features made children unable to communicate symptoms.

One child (child four) had received monovalent measles vaccine at 15 months, after which his development slowed (confirmed by professional assessors). No association was made with the vaccine at the time. He received a dose of measles, mumps, and rubella vaccine at age 4·5 years, the day after which his mother described a striking deterioration in his behaviour that she did link with the immunisation. Child nine received measles, mumps, and rubella vaccine at 16 months. At 18 months he developed recurrent antibiotic-resistant otitis media and the first behavioural symptoms, including disinterest in his sibling and lack of play.

Table 2 summarises the neuropsychiatric diagnoses; the apparent precipitating events; onset of behavioural features; and age of onset of both behaviour and bowel symptoms.

Laboratory tests

All children were antiendomyseal-antibody negative and common enteric pathogens were not identified by culture, microscopy, or serology. Urinary methylmalonic-acid excretion was significantly raised in all eight children who

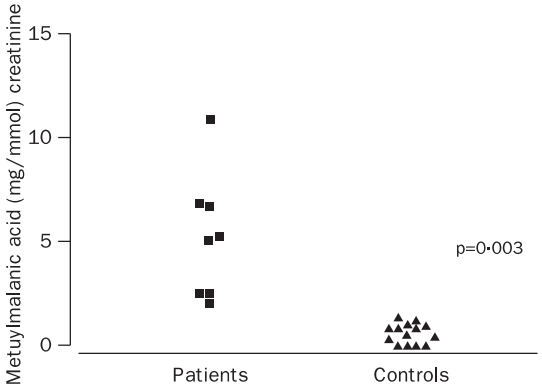


Figure 1: **Urinary methylmalonic-acid excretion in patients and controls**

p=Significance of mean excretion in patients compared with controls.

Child	Behavioural diagnosis	Exposure identified by parents or doctor	Interval from exposure to first behavioural symptom	Features associated with exposure	Age at onset of first symptom	
					Behaviour	Bowel
1	Autism	MMR	1 week	Fever/delirium	12 months	Not known
2	Autism	MMR	2 weeks	Self injury	13 months	20 months
3	Autism	MMR	48 h	Rash and fever	14 months	Not known
4	Autism? Disintegrative disorder?	MMR	Measles vaccine at 15 months followed by slowing in development. Dramatic deterioration in behaviour immediately after MMR at 4·5 years	Repetitive behaviour, self injury, loss of self-help	4·5 years	18 months
5	Autism	None—MMR at 16 months	Self-injurious behaviour started at 18 months		4 years	
6	Autism	MMR	1 week	Rash & convulsion; gaze avoidance & self injury	15 months	18 months
7	Autism	MMR	24 h	Convulsion, gaze avoidance	21 months	2 years
8	Post-vaccinial encephalitis?	MMR	2 weeks	Fever, convulsion, rash & diarrhoea	19 months	19 months
9	Autistic spectrum disorder	Recurrent otitis media	1 week (MMR 2 months previously)	Disinterest; lack of play	18 mont	ars
10	Post-viral encephalitis?	Measles (previously vaccinated with MMR)	24 h	Fever, rash & vomiting	15 ths	Not kn
11	Autism	MMR	1 week	Recurrent "viral pneumonia" for 8 weeks following MMR	15 mon	Not know
12	Autism	None—MMR at 15 months	Loss of speech development and deterioration in language skills noted at 16 months			Not known

MMR=measles, mumps, and rubella vaccine.

Table 2: **Neuropsychiatric diagnosis**

were tested, compared with age-matched controls (p=0·003; figure 1). Abnormal laboratory tests are shown in table 1.

Endoscopic findings

The caecum was seen in all cases, and the ileum in all but two cases. Endoscopic findings are shown in table 1. Macroscopic colonic appearances were reported as normal in four children. The remaining eight had col ic and rectal mucosal abnormalities including granular loss of vascular pattern, patchy erythema, lympho nodular hyperplasia, and in two cas phthoid ulceration. Four cases showed the "red h " sig round swollen caecal lymphoid follicles, a early en scopic feature of Crohn's disease.[3] The st consistent feature was lymphoid odula perplasia of the terminal ileum which w seen in e children (figure 2), and identified by n follow-thro h in one other child in whom th ileum as not reached at endoscopy. The nor endoscopic ppearance of the terminal ileum (fig e 2) was seen in seven children whose images we available for comparison.

Histological findi

Histolo dings summ ised in table 1.

Ter al ileum A reactive mphoid follicular hyperplasia wa resent i ileal biopsies of seven children. In each case, an than three expanded and confluent lymphoid follicles ith reactive germinal centres were identified within the issue section (figure 3). There was no neutrophil in rate and granulomas were not present.

Colon The lamina propria was infiltrated by mononuclear cells (mainly lymphocytes and macrophages) in the colonic-biopsy samples. The extent ranged in severity from scattered focal collections of cells beneath the surface epithelium (five cases) to diffuse infiltration of the mucosa (six cases). There was no increase in intraepithelial lymphocytes, except in one case, in which numerous lymphocytes had infiltrated the surface epithelium in the proximal colonic biopsies. Lymphoid follicles in the vicinity of mononuclear-cell infiltrates showed en ged erminal cen with reactive changes that included an ex s of tingible body macrophages.

There was no clear relation between the endoscopic ap arances and the istological findings; chronic i ammatory changes were apparent histologically in e doscopically rmal areas of the colon. In five cases t e was focal ute inflammation with infiltration of the lam a propri by neutrophils; in three of these, neutro filtrated the caecal (figure 3) and rectal-pt epithelium. There were no crypt abscesses. Occa al bifid crypts were noted but overall crypt architecture was normal. There was no goblet-cell depletion but occasional collections of eosinophils were seen in the mucosa. There were no granulomata. Parasites and organisms were not seen. None of the changes described above were seen in any of the normal biopsy specimens.

Discussion

We describe a pattern of colitis and ileal-lymphoid-nodular hyperplasia in children with developmental disorders. Intestinal and behavioural pathologies may have occurred together by chance, reflecting a selection bias in a self-referred group; however, the uniformity of the intestinal pathological changes and the fact that previous studies have found intestinal dysfunction in children with autistic-spectrum disorders, suggests that the connection is real and reflects a unique disease process.

Asperger first recorded the link between coeliac disease and behavioural psychoses.[4] Walker-Smith and colleagues[5] detected low concentrations of alpha-1 antitrypsin in children with typical autism, and D'Eufemia and colleagues[6] identified abnormal intestinal permeability, a feature of small intestinal enteropathy, in 43% of a group of autistic children with no gastrointestinal symptoms, but not in matched controls. These studies, together with our own, including evidence of anaemia and IgA deficiency in some children, would support the hypothesis that the consequences of an inflamed or dysfunctional intestine may play a part in behavioural changes in some children.

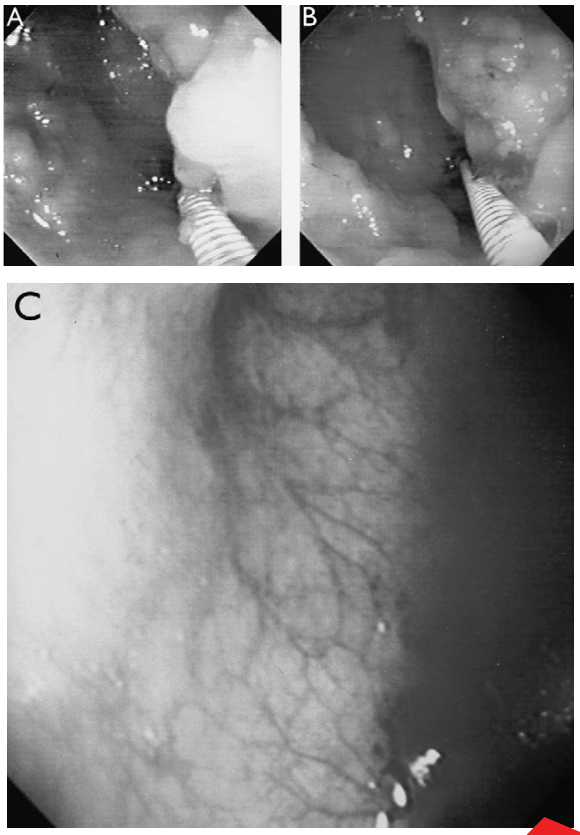
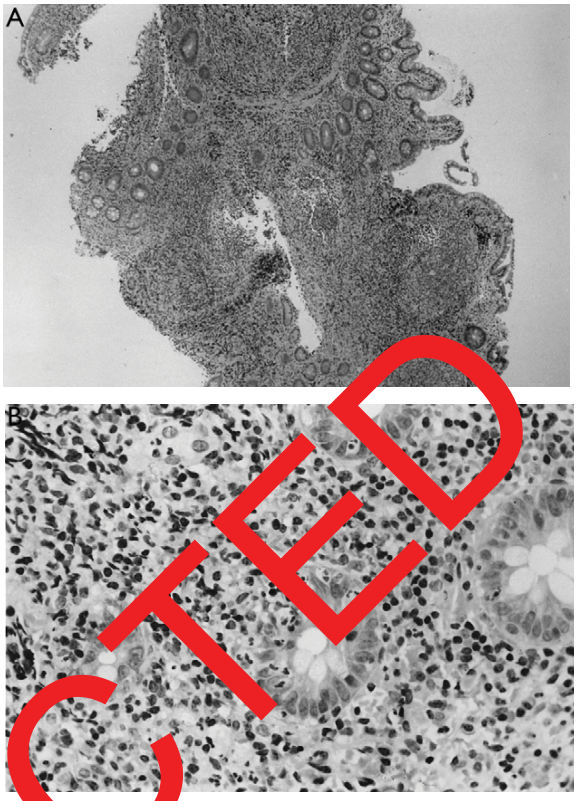


Figure 2: **Endoscopic view of terminal ilium in child three a[illegible] in a child with endoscopically and histologically normal ileu[illegible] and colon**

Greatly enlarged lymphoid nodule in right-hand field of vi[illegible] and B=child three; C=normal ileum. Remainder of mucosa[illegible] terminal ileum is a carpet of enlarged lymphoid no[illegible]s.



Figu[illegible]: **Biops[illegible]ample from terminal ileum (top) and from colon (b[illegible])**

[illegible]hild three; lymphoid hyperplasia with extensive, confluent lymphoid [illegible]; B=child three; dense infiltration of the lamina propria crypt epithelium by neutrophils and mononuclear cells. Stained with haematoxylin and eosin.

The "opioid excess" theory of a[illegible]ism[illegible] by Panksepp and colleagues[7] [illegible] later b[illegible]eichelt and colleagues[8] and Shattock a[illegible]olleagues[9] p[illegible]oses that autistic disorders result fr[illegible] th[illegible]incomplete b[illegible]akdown and excessive absorption of gut-d[illegible]ved peptides from foods, including bar[illegible], rye, oats, an[illegible]aesin from milk and dairy produc[illegible] These peptides ma[illegible] exert central-opioid effects, [illegible]irectly [illegible] through the formation of ligands with pep[illegible]ase[illegible]izymes required for breakdown of endogenous cen[illegible]-nervous[illegible]stem opioids,[9] leading to dis[illegible]ptio[illegible]of no[illegible]al [illegible]uroregulation and brain devel[illegible]pment b[illegible] endogen[illegible]ncephalins and endorphins. [illegible]e aspec[illegible]f impaired intestinal function that could perm[illegible]inc[illegible]ased pe[illegible]eability to exogenous peptides is deficien[illegible] of the phenyl-sulphur-transferase systems, as described [illegible]y Waring.[10] The normally sulphated glycoprotein [illegible]atrix of the gut wall acts to regulate cell and molecular trafficking.[11] Disruption of this matrix and increased intestinal permeability, both features of inflammatory bowel disease,[17] may cause both intestinal and neuropsychiatric dysfunction. Impaired enterohepatic sulphation and consequent detoxification of compounds such as the phenolic amines (dopamine, tyramine, and serotonin)[12] may also contribute. Both the presence of intestinal inflammation and absence of detectable neurological abnormality in our children are consistent with an exogenous influence upon cerebral function. Lucarelli's observation that after removal of a provocative enteric antigen children achieved symptomatic behavioural improvement, suggests a reversible element in this condition.[13]

Despite consistent gastrointestinal findings, behavioural changes in these children were more heterogeneous. In some cases the onset and course of behavioural regression was precipitous, with children losing all communication skills over a few weeks to months. This regression is consistent with a disintegrative psychosis (Heller's disease), which typically occurs when normally developing children show striking behaviour changes and developmental regression, commonly in association with some loss of coordination and bowel or bladder function.[14] Disintegrative psychosis is typically described as occurring in children after at least 2–3 years of apparently normal development.

Disintegrative psychosis is recognised as a sequel to measles encephalitis, although in most cases no cause is ever identified.[14] Viral encephalitis can give rise to autistic disorders, particularly when it occurs early in life.[15] Rubella virus is associated with autism and the combined measles, mumps, and rubella vaccine (rather than monovalent measles vaccine) has also been implicated. Fudenberg[16] noted that for 15 of 20 autistic children, the first symptoms developed within a week of vaccination. Gupta[17] commented on the striking association between measles, mumps, and rubella vaccination and the onset of behavioural symptoms in all the children that he had investigated for regressive autism. Measles virus[18,19] and measles vaccination[20] have both been implicated as risk

factors for Crohn's disease and persistent measles vaccine-strain virus infection has been found in children with autoimmune hepatitis.[21]

We did not prove an association between measles, mumps, and rubella vaccine and the syndrome described. Virological studies are underway that may help to resolve this issue.

If there is a causal link between measles, mumps, and rubella vaccine and this syndrome, a rising incidence might be anticipated after the introduction of this vaccine in the UK in 1988. Published evidence is inadequate to show whether there is a change in incidence[22] or a link with measles, mumps, and rubella vaccine.[23] A genetic predisposition to autistic-spectrum disorders is suggested by over-representation in boys and a greater concordance rate in monozygotic than in dizygotic twins.[15] In the context of susceptibility to infection, a genetic association with autism, linked to a null allele of the *complement (C) 4B* gene located in the class III region of the major-histocompatibility complex, has been recorded by Warren and colleagues.[24] *C4B*-gene products are crucial for the activation of the complement pathway and protection against infection: individuals inheriting one or two *C4B* null alleles may not handle certain viruses appropriately, possibly including attenuated strains.

Urinary methylmalonic-acid concentrations were raised in most of the children, a finding indicative of a functional vitamin B12 deficiency. Although vitamin B12 concentrations were normal, serum B12 is not a good measure of functional B12 status.[25] Urinary methylmalonic-acid excretion is increased in disorders such as Crohn's disease, in which cobalamin excreted in bile is not reabsorbed. A similar problem may have occurred in the children in our study. Vitamin B12 is essential for myelinogenesis in the developing central nervous system, a process that is not complete until around the age of 10 years. B12 deficiency may, therefore, be a contributory factor in the developmental regression.[26]

We have identified a chronic enterocolitis in children that may be related to neurological or psychiatric dysfunction. In most cases, onset of symptoms was after measles, mumps, and rubella immunisation. Further investigations are needed to examine this syndrome and its possible relation to this vaccine.

Addendum:
Up to Jan 28, a further 40 patients have been assessed; 39 with the syndrome.

Contributors
A J Wakefield was the senior scientific investigator. S H Murch and M A Thomson did endoscopies. A Anthony, A P Dhillon, and S E Davies carried out the histopathology. J Linnell did the B12 studies. D M Casson and M Malik did the clinical assessment. M Berelowitz did the psychiatric assessment. P Harvey did the neurological assessment. A Valentine did the radiological assessment. JW-S was the senior clinical investigator.

Acknowledgments
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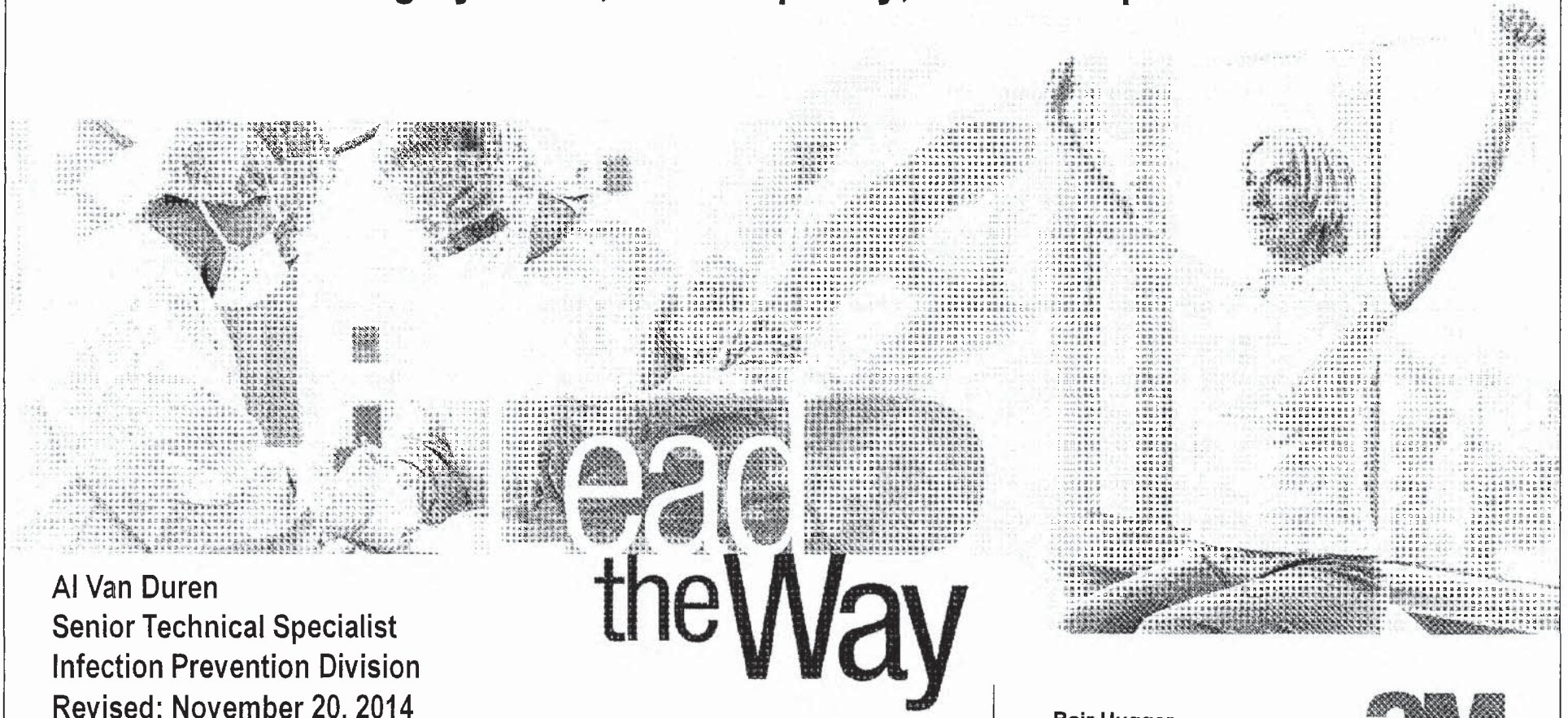
EXHIBIT DX34

TO DECLARATION OF COREY L. GORDON IN SUPPORT OF DEFENDANTS' OPPOSITION TO PLAINTIFFS' MOTIONS TO EXCLUDE TESTIMONY OF THEODORE HOLFORD AND JONATHAN BORAK

Forced-air warming systems, OR air quality, and orthopedic SSI



Al Van Duren
Senior Technical Specialist
Infection Prevention Division
Revised: November 20, 2014
3M Infection Prevention Solutions

Bair Hugger
Exhibit 76
Date: 11-7-16
Richard G. Stirewalt
Stirewalt & Associates

Conclusions

- LAF / ultraclean air systems reduce the airborne particulates; however, the protective effect is dubious.
- Current SSI rates in TKA and THA are very low; typically < 1%
- The airborne route does not appear to be a clinically significant route of infection in modern orthopedic surgery.
- Forced air warming systems do not worsen OR air quality.[1,2]
- Host defenses play an important role in infection prevention.
- Perioperative normothermia is essential for an adequate immune response, and It also reduces morbidity and mortality from other causes.[3]

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EXHIBIT DX35

TO DECLARATION OF COREY L. GORDON IN SUPPORT OF DEFENDANTS' OPPOSITION TO PLAINTIFFS' MOTIONS TO EXCLUDE TESTIMONY OF THEODORE HOLFORD AND JONATHAN BORAK

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Infection Control In Orthopaedic Surgery

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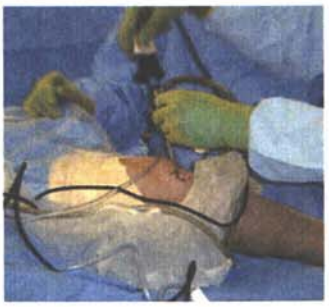

What is the latest best practice on reducing surgical site infection in orthopaedic surgery? ANDREW BRISTER reports on the findings from a recent symposium.

One infection is one too many, ran the slogan behind Ethicon's Surgical Site Infection Symposium at the ICC, Birmingham. There can be no doubting that hospitals across the country are committed to doing all they can to stop infection, yet lives continue to be blighted by surgical site infections, resulting in extended hospital stays for patients and huge costs for the NHS. Estimates put the cost of healthcare associated infections Europe-wide at Z6.3 million each year, with patients spending, on average, an extra 6.5 days in hospital. A 10% reduction in the infection rate could save Z150 m every year, more than 360,000 bed days and nearly 48,000 consultant sessions. The symposium brought together leading experts in the field of surgical site infection, and featured two presentations looking at orthopaedic surgery, where 'taking responsibility for infection' was the order of the day. Rhidian Morgan-Jones, a consultant at the University Hospital of Wales and Cardiff, said: "As surgeons we need to put our hands up and admit that we cannot blame the patient, we cannot blame the theatre, or theatre staff. Surgeons need to take responsibility for infection too and this should provide a good building block to improve our practices." One of Mr Morgan-Jones' specialisms is knee replacement and revision of failed knee replacements. "There are 70,000 knee replacements per year in the UK. Deep infection rates can vary from 0.5% to up to 2%. On average, this results in 700 cases of serious infection each year in knee replacements alone." So, what measures can be taken to avoid infection? Mr Morgan-Jones suggests that one solution is not to operate. He explained his reasoning: "Every time you operate there is a risk of infection." He offered the audience an example, using the case of a low energy break in the tibia, where a surgeon had made the decision to operate, inserting metalwork into the leg. The patient subsequently suffered from an infection. Mr Morgan-Jones suggested that, in this case, the bone would have healed without the need for surgical intervention if it had simply been left in plaster. In cases where surgery is unavoidable, Mr Morgan-Jones advised that tourniquets should be used for the shortest time possible suggesting that, for a knee replacement, a tourniquet should not be on for more than an hour, lessening the risk of infection. He also advised Trusts to consider moving to disposable single-use tourniquets. "Sometimes you do not have to use tourniquets on certain knee operations," said Mr Morgan-Jones. "I use them because I like to have a bloodless field when I am working or cementing. However, they should not be used if the patient has a vascular disease."

Surgical technique

Surgical techniques will also have an impact on infection. "We went through a phase of minimally-invasive surgery," said Mr Morgan-Jones. "The wounds were worse, the positions of the implants were worse and we have now moved away from this type of surgery. Small incisions should be an outcome of good surgery; it should not be a primary goal." Mr Morgan-Jones and his team at Cardiff have pioneered a tibial crest osteotomy with a suture technique that eliminates the need for screws or wires which can cause their own problems once you close the osteotomy. "This has revolutionised the practice of knee replacement in Cardiff," he said. On sutures, Mr Morgan-Jones recommended that large knots should be minimised and absorbable sutures be used where possible. He also favours antibacterial sutures, such as Vicryl Plus. Staples may be necessary when skin quality is very poor and a suture is not going to hold. "Skin staples produce irritation and compression and can cause superficial infection, although there is no evidence of deep infection," he said. Mr Morgan-Jones now uses the Aquacel absorbent dressing which absorbs and interacts with wound exudates to form a soft, hydrophilic, gas-permeable gel that traps bacteria and conforms to the contours of the wound. "Why Aquacel? It is absorbent. Wounds are going to leak and you want to absorb that leak." Mr Morgan-Jones also has a fiveday rule on dressing changes for knee replacements. "No nurse is allowed to change the dressing within the first five days without prior discussion. Wounds heal if you leave them alone, but not if you take the dressing off to have a look at them. That, more than anything else will increase the risk of infection," he said. "Five days is the length of time before patients are sent home following a knee replacement, so we change the dressing before the patient goes home." There is a significant debate in orthopaedic surgery about thromboprophylaxis and the need for anti-thrombotic drugs. The National Institute for Health and Clinical Excellence (NICE) prescribes the use of oral Factor Xa inhibitors to reduce the rate of pulmonary embolisms (PE). "We have found that these drugs do work. They halved the PE rate, but made no difference to the incidence rate of deep vein thrombosis and doubled the haematoma rate and the return to theatre rate," said Mr Morgan-Jones. "There is an advantage to these drugs and there is a big disadvantage. We need to be careful about following guidelines. As a community in Cardiff, we are starting to move back towards aspirin."

Antibiotics

Antibiotics are another emotive issue. Mr Morgan-Jones warned against reliance on them. He said: "A colleague once said to me: 'Antibiotics will make a third rate surgeon into a second rate one.' Surgeons should not rely on antibiotics to do their job for them. They offer us a useful tool, but are not a substitute for good practice." He favours short course duration – five days intravenously, followed by six weeks orally, with the oral drugs being dual therapy. Mr Morgan-Jones has pioneered a radical single-stage operation for infected knee replacements. "Although two-stage surgery is the standard across the country, we have done nothing but one-stage surgery for the last three years and I would not go back to two-stage." For other types of orthopaedic surgery too, he presented many cases where radical surgery has proved to offer the only solution to long-standing cases of infection. Cleaning of the wound is paramount. Mr Morgan-Jones showed his compartmental debridement technique, reaming from the top to the bottom to clean-up the entire middle of the bone before copiously washing with lavage. Then comes the carbojet, effectively blow drying the wound with carbon dioxide under pressure. This allows any last bits of membrane and biofilm to be more readily removed before washing and drying again until clear. Mr Morgan-Jones also showed his modified Papineau technique for the treatment of chronic open osteomyelitis of the tibia, named after the French-Canadian famed for leaving big wounds open. "I am quite happy to leave the bone exposed," said Mr Morgan-Jones. "If it has a blood supply it will heal. Wounds heal because you have cleaned out the rubbish. We have carried out 15 operations in this way and they have all healed well." Mr Morgan-Jones also called for more work to be done in multidisciplinary teams to deal with orthopaedic infection. "We have to start talking to each other. I don't want to be a one-man band. I need help from the microbiologists, the pharmacists, the radiologists, the dieticians. There has to be teamwork."

Introducing changes

Mike Reed is a consultant orthopaedic surgeon at Northumbria Healthcare (UK), and chairs the Orthopaedic Surgical Site Infection Committee, which has significantly reduced the rates of infections within the Trust. "Infection is like a grief reaction. It is something that we take very seriously, but it is something that we are also in denial about. Denial is the biggest barrier to success in any joint infection reduction programme," said Mr Reed. "We set up the SSI group with a lot of power to make changes. Every deep infection now gets a root cause analysis and far-reaching changes have been implemented." One pre-operative measure is to decolonise patients for all Staphylococcus aureus, not just MRSA. "It is a leap of faith to get management to test for this as well as MRSA but if you can make this happen in your hospitals you will reduce infection rates," said Mr Reed. His findings are backed up by a study in the New England Journal of Medicine in January 2010. "Patient warming is critical", stressed Mr Reed. "The main aim is to keep patients normothermic during and after surgery when the risk is high. Again, this is supported by studies in the New England Journal of Medicine (1996) and The Lancet (2001). We have further introduced pre-warming, via conductive electric blankets, for half an hour prior to surgery." Theatre maintenance is also a significant issue. On the operating table, Mr Reed highlighted the importance of working within the laminar flow afforded by an overhead ventilating canopy. Studies have shown that outside the laminar flow particle counts soar from zero to 600,000 per cubic metre – not surprising when each person sheds some one million skin cells per day. For skin preparation, Mr Reed has moved away from traditional aqueous povidone-iodine to the use of chlorohexidine with alcohol. "If your surgeon is still using iodine plus alcohol then there is a very robust study that shows that they could do better. Read it and ask them about it," advised Mr Reed. Antibiotic choice has proved to be a minefield since Clostridium difficile came along. "We stopped using Cefuroxime, on the insistence of our chief executive, to reduce C. difficile. Yes, we went from three cases per 1,000 of C. difficile to zero, but our infection rate doubled when we went to Gentamicin. There is no hard evidence to tell us what antibiotics we should be using. It is a really difficult problem and we need a trial," urged Mr Reed. It is also difficult to know what to do with dressings, thought Mr Reed. A study by Glasgow's Golden Jubilee Hospital showed that its own Jubilee dressing design achieved a dramatic reduction in blisters, compared to standard dressings. A randomised trial showed a decrease in surgical site infection rates from 3.2% to 0.8%. "That was good enough for me and we changed Trust-wide," said Mr Reed. Like Mr Morgan-Jones, Mr Reed found the issue of thromboprophylaxis to be a great source of contention. "We changed to Rivaroxaban from Tinzaparin and found that returns to theatres from wound complications more than doubled," said Reed. Studies at 10 other hospitals have also shown an increase in wound complications from Rivaroxaban. "We would rather use aspirin, but NICE guidelines constrain us." In treatment rooms, Northumbria has installed small boxes that suck air in, shine UV light to sterilise it and blow the air back out again. "A randomised trial showed a significant reduction in colony counts in treatment rooms. Apparently, they are also effective on C. difficile, although we did not test for that," said Mr Reed. Overall, Mr Reed admits that the strategy needed some tweaks along the way. For example, on pre-warming it took the team a while to move to conductive fabric from forced air warming. Mr Reed's studies with tiny air bubbles on a mock-up theatre proved that forced air warming interferes with the laminar flow from the clean air canopy. Infection rates have significantly improved at the Trust since implementing these measures, but Mr Reed is not resting on his laurels. The latest steps are looking at improved technique, with audited analysis of surgeons. The team is also conducting a randomised trial on the use of ordinary cement versus high dose antibiotic cement in hip fracture hemiarthroplasty. Interim results have shown a very significant reduction in superficial infection rates, down from 2.9% to zero, but no significant reduction in deep infection rates (2.9% to 2.1%). A randomised trial of Vicryl Plus is also being carried out.

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Centenary Pavilion, Elland Road Stadium, Leeds
Wednesday 12th July 2017

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